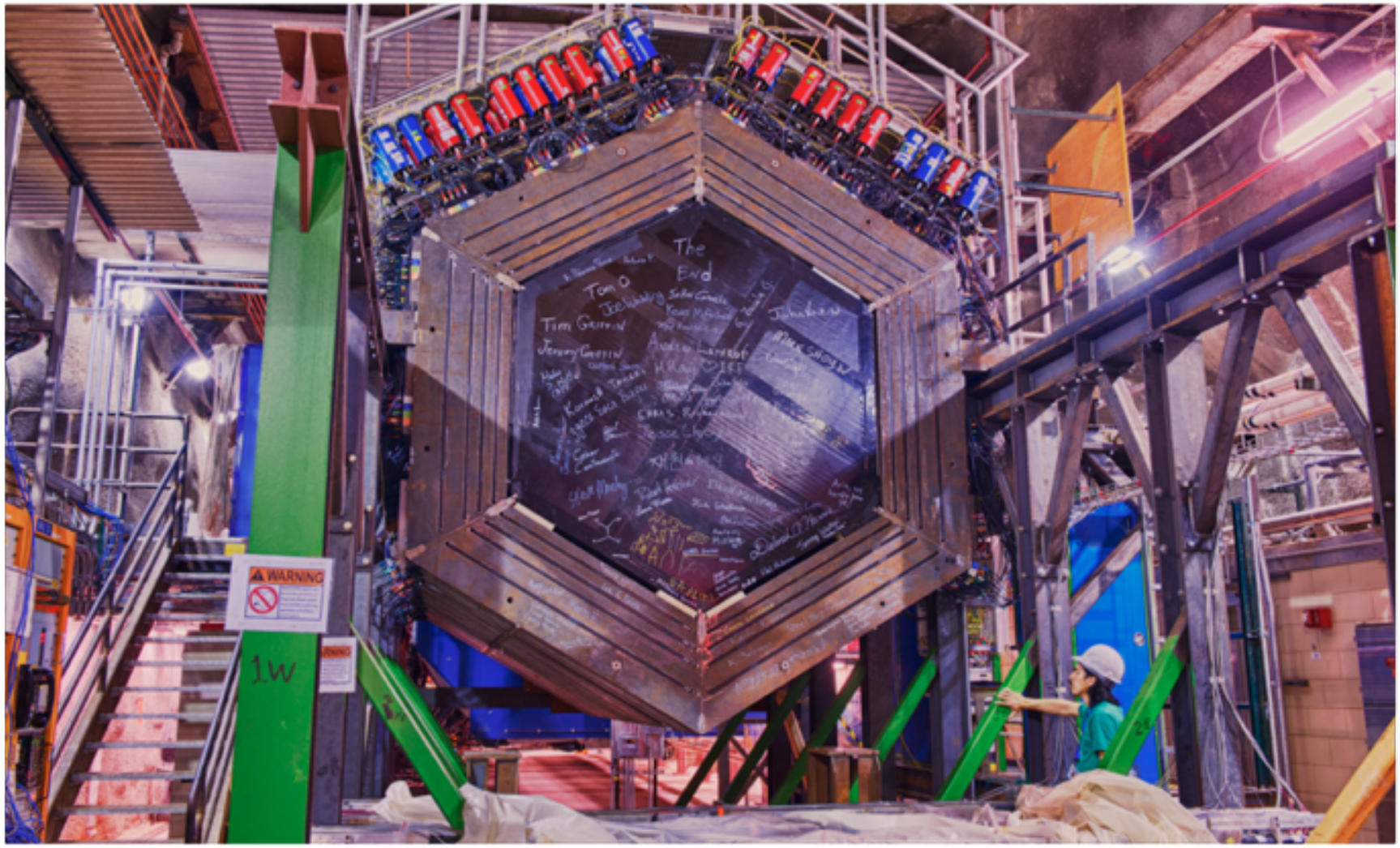


Recent Results from MINERνA

2014 Fermilab User's Meeting

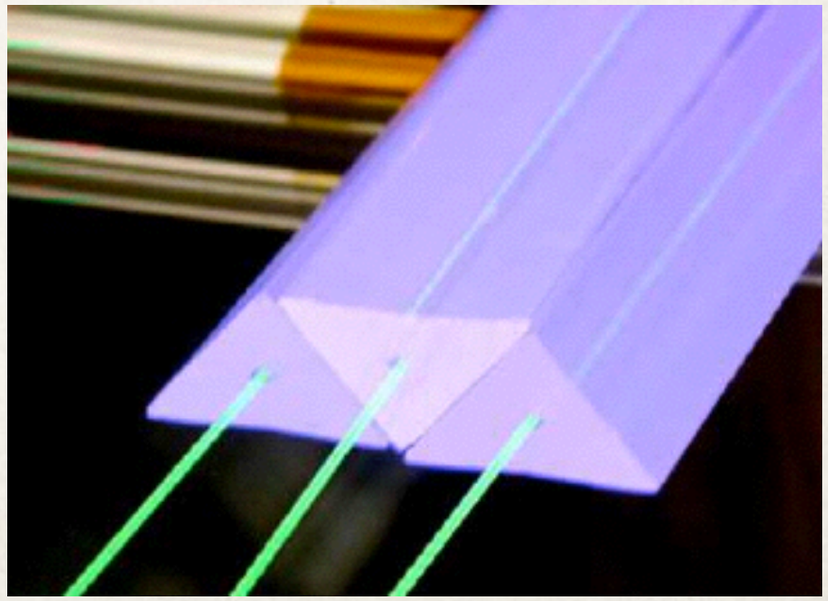
Laura Fields, Northwestern
For the MINERvA Collaboration

12 June 2014

MINERvA Overview

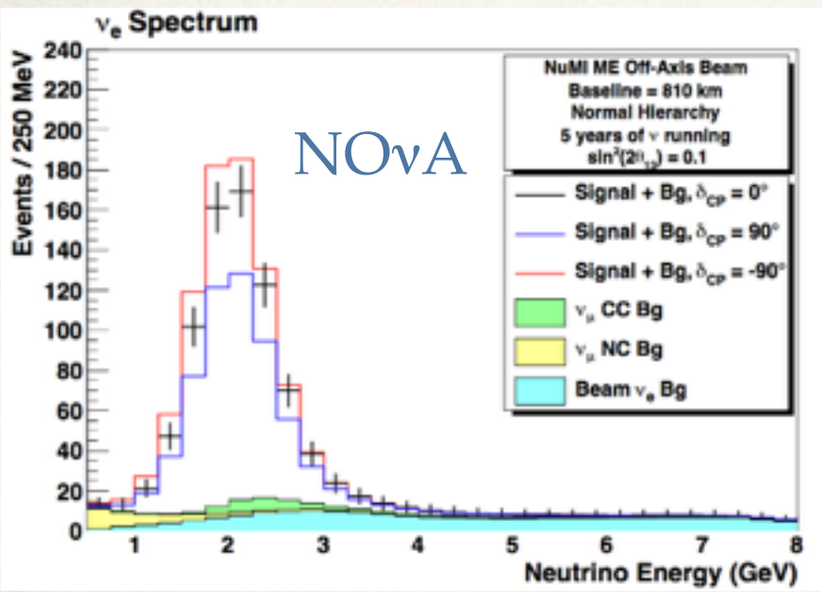
- MINERvA is a high resolution neutrino detector that sits in the NuMI beam line just upstream of the MINOS near detector

- Designed to make precision measurements of neutrino interaction cross sections for E_ν ~ 1 - 20 GeV

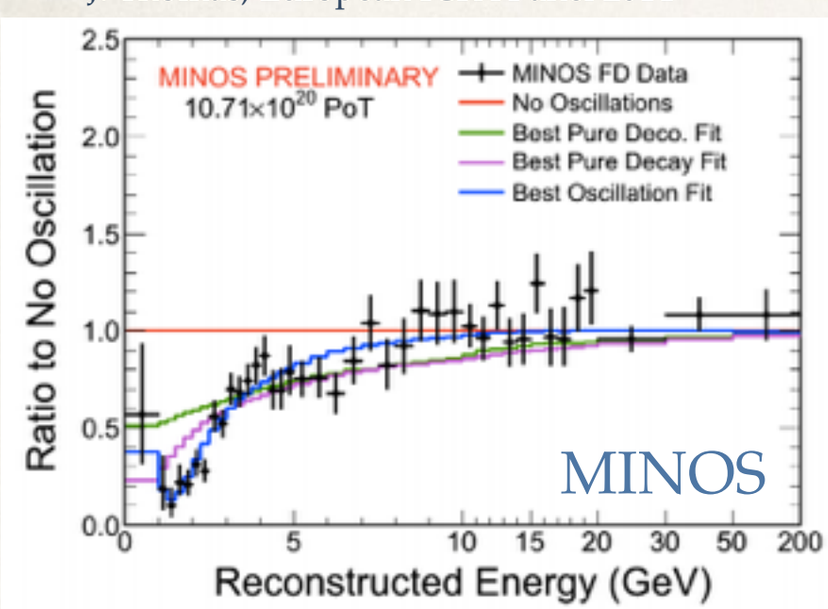


MINERνA Motivation

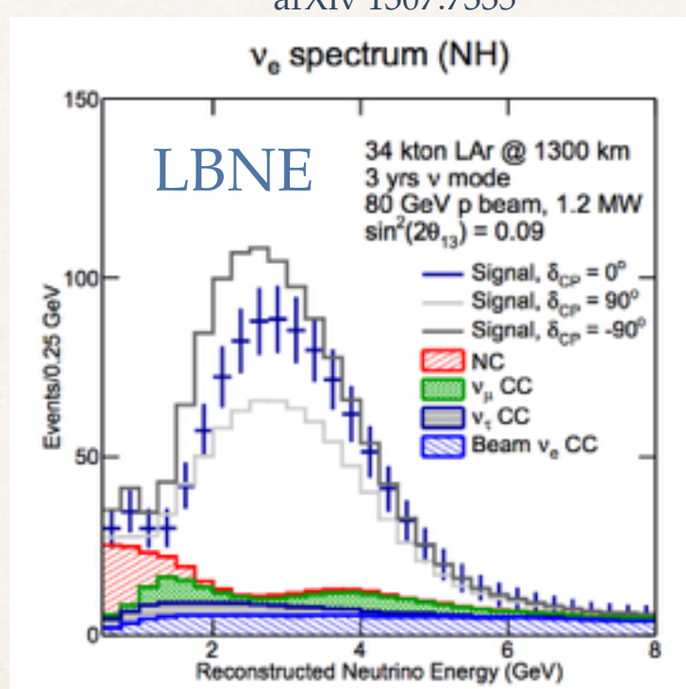
- Measuring neutrino interaction cross sections facilitates high precision neutrino oscillation measurements:



J. Thomas, European ICFA Panel 2014



arXiv 1307.7335



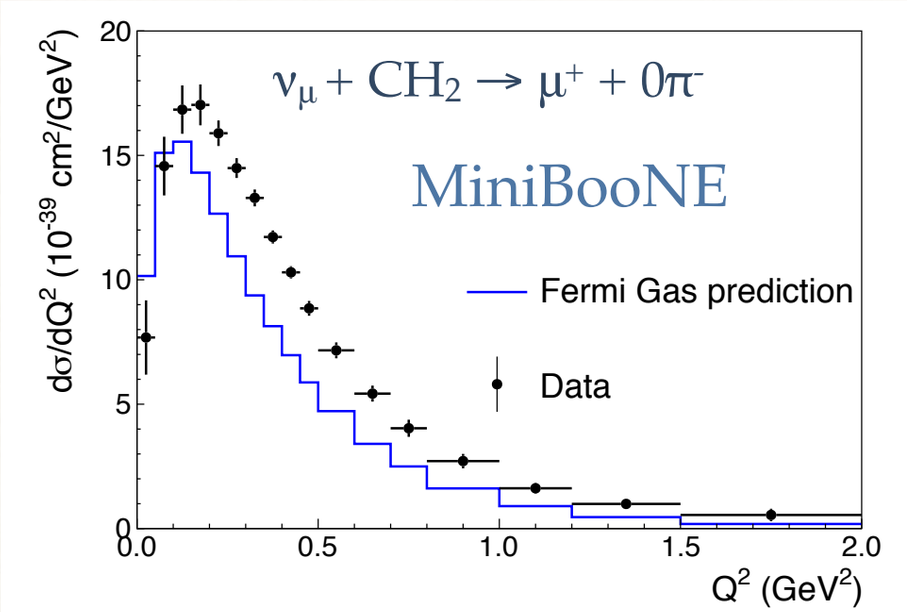
This morning we've seen many comparisons of data to **predictions given various oscillation scenarios**

These predictions require a model of neutrino interactions in matter

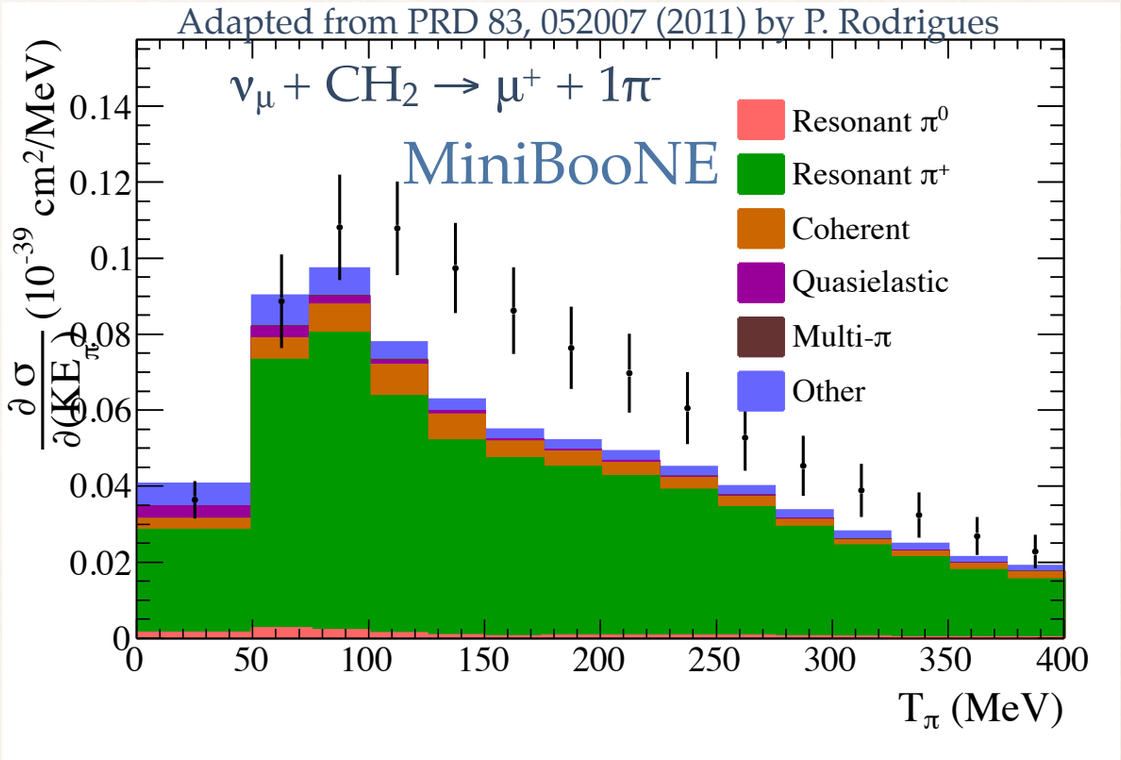
MINERνA Motivation

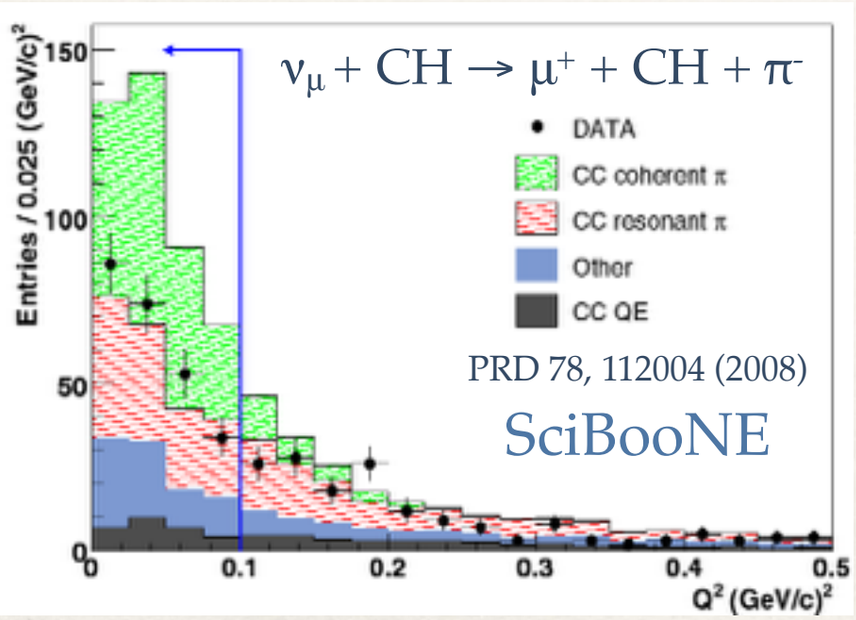
- The predictions you've seen this morning use models which do not accurately reflect cross section data

Adapted from PRD 81, 092005 (2010) by P. Rodrigues



Adapted from PRD 83, 052007 (2011) by P. Rodrigues



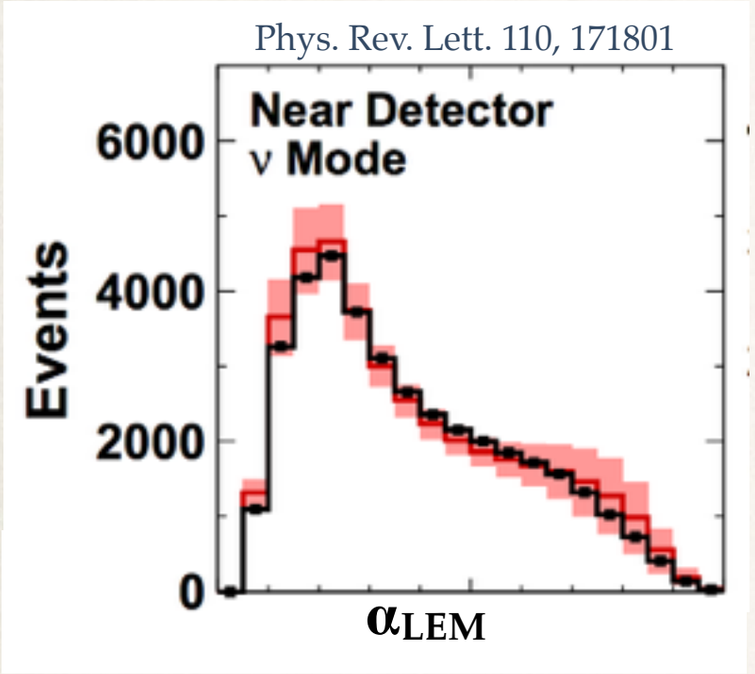


- These disagreements with data lead directly to systematic uncertainties in oscillation measurements

MINERνA Overview

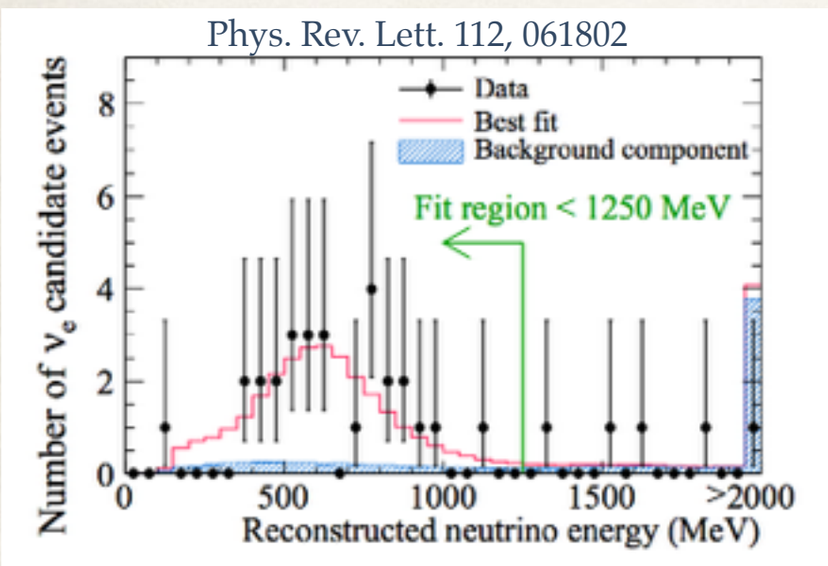
Recent uncertainties on signal predictions in ν_e appearance measurements:

Phys. Rev. Lett. 110, 171801



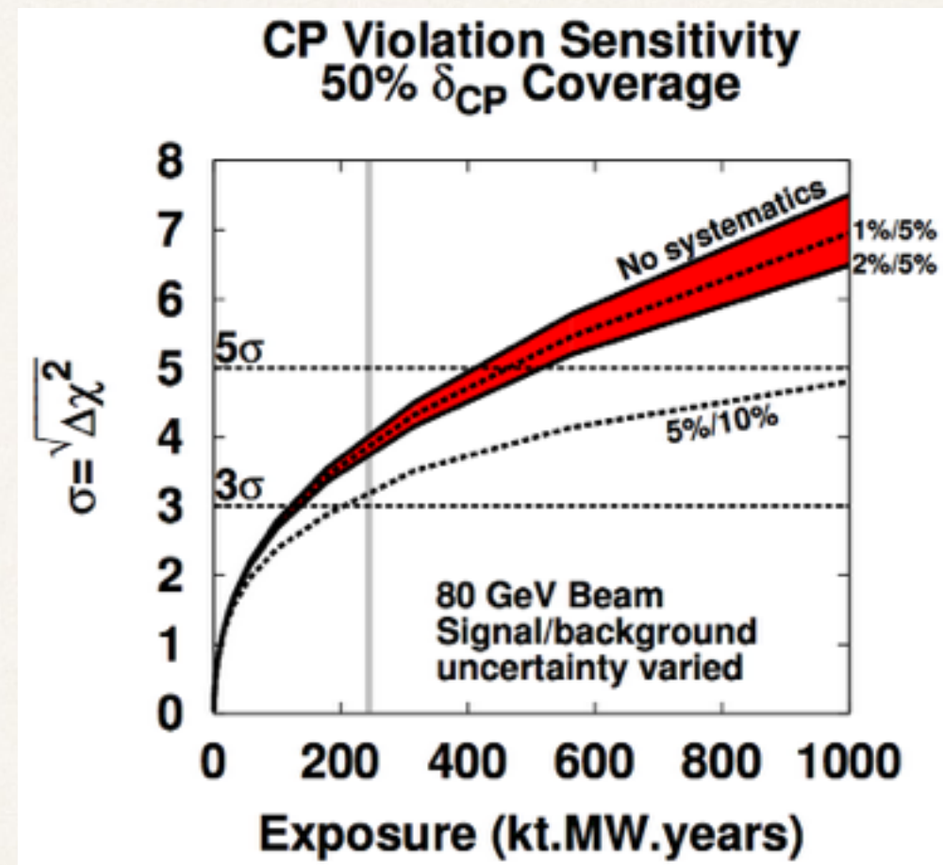
MINOS uncertainty on signal prediction = 5.6%

Phys. Rev. Lett. 112, 061802



T2K (signal dominated) uncertainty on MC prediction = 8.8%

M. Bass NuInt 2014

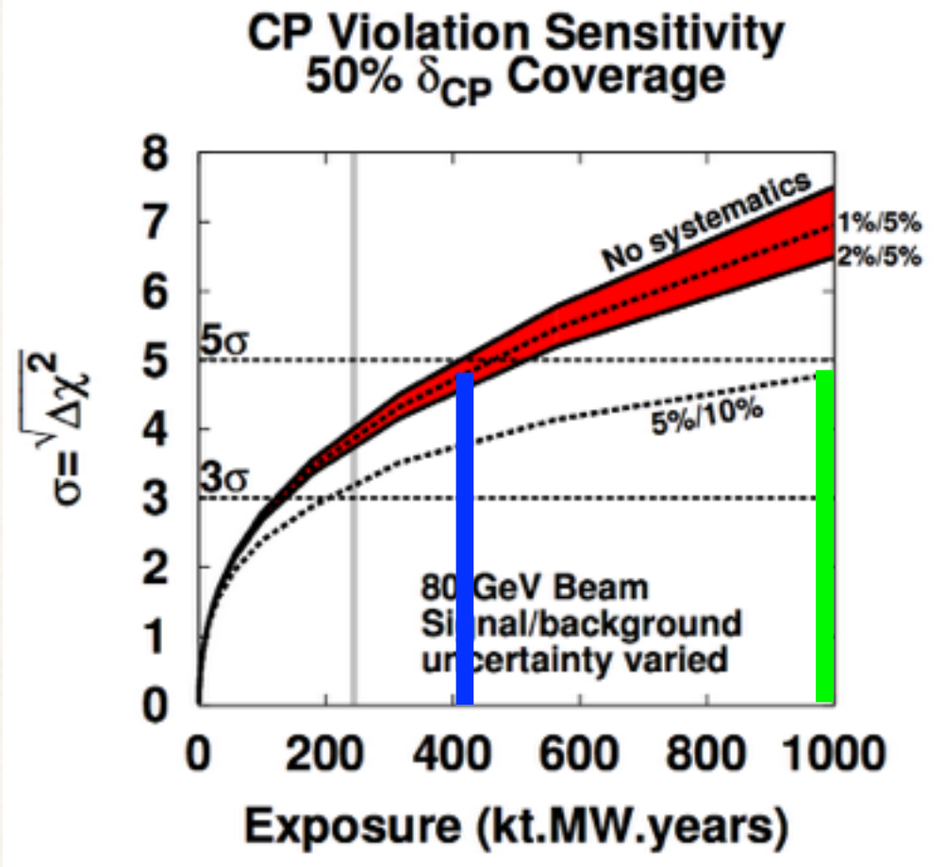


- LBNE's goal is 1% for total systematic uncertainty on signal prediction
- Sensitivity to CP violation is strongly impacted by uncertainty on signal (and background) predictions

MINERνA Overview

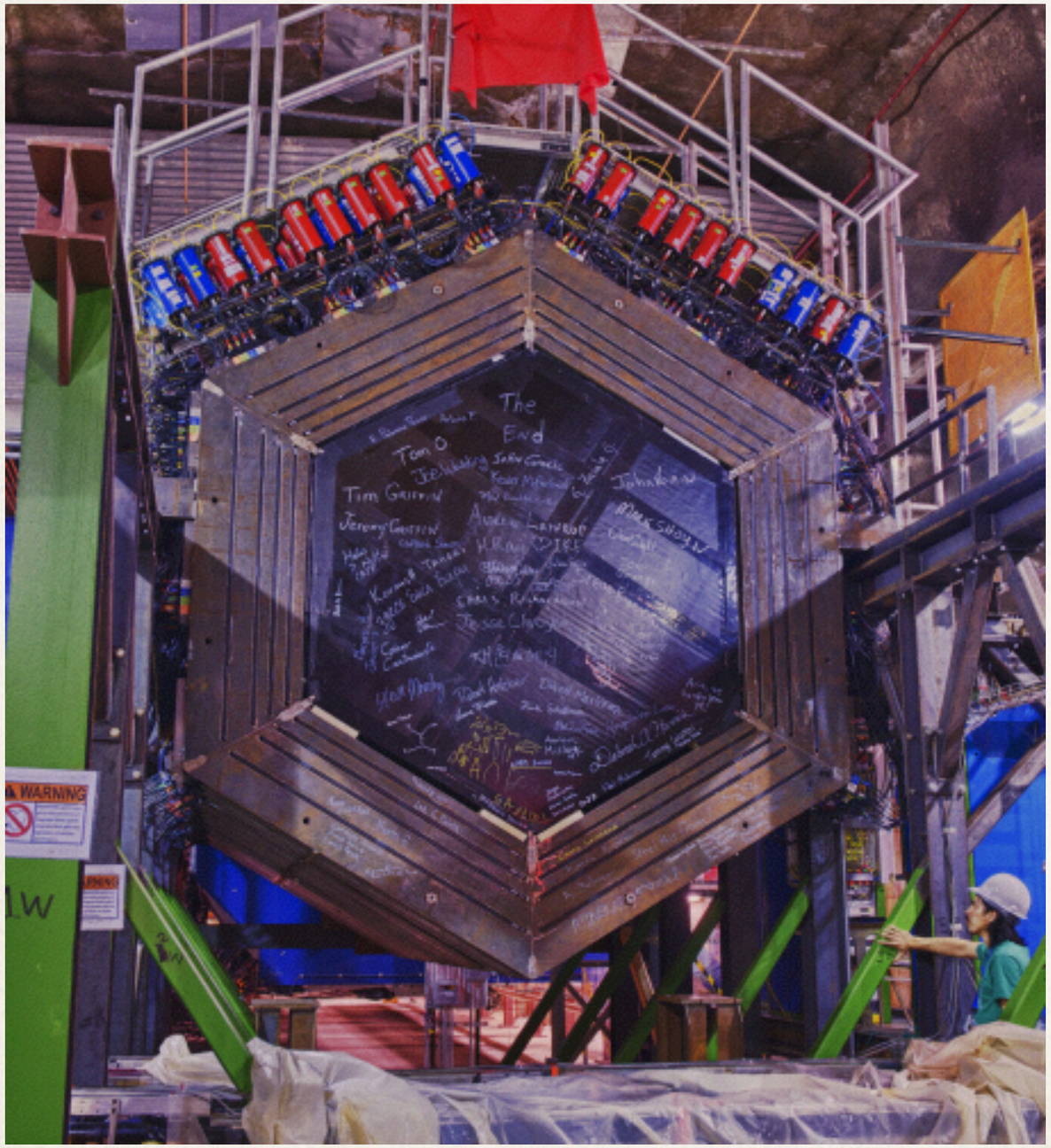
The difference between LBNE's signal systematics goal of 1% and the current state of the art (~5%) is the difference between getting to nearly 5σ for 50% of possible values of δ_{CP} in 10 years rather than 25

M. Bass NuInt 2014



10 years	25 years
x 1.2 MW	x 1.2 MW
x 34 kTon	x 34 kTon

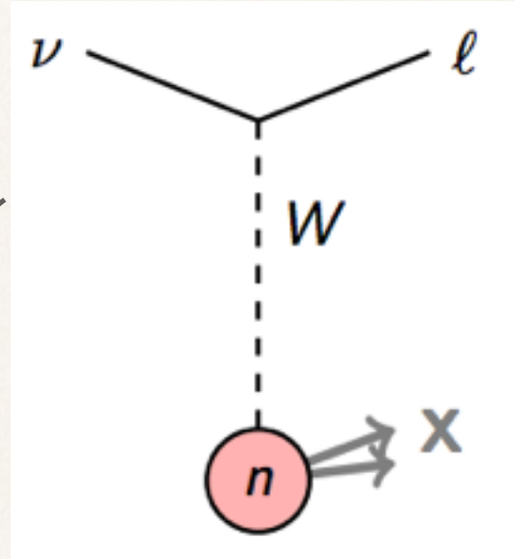
MINERνA Overview



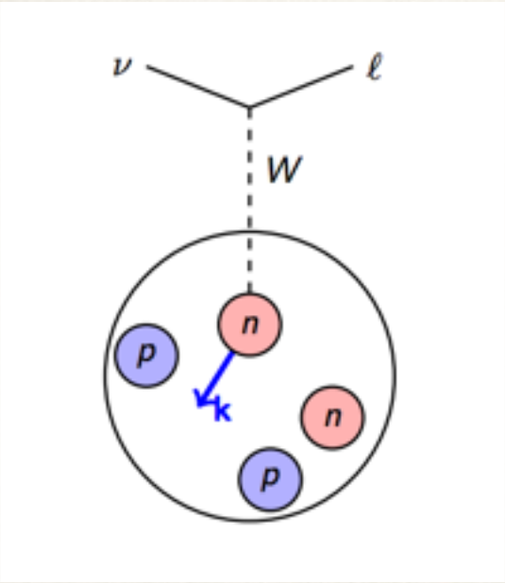
- We need better models and high precision data to constrain these models
- The MINERνA detector was designed to provide such data
  - High precision cross section measurements in the region of interest to oscillation experiments (~1-10 GeV)
  - Detailed descriptions of final state particles

MINERνA Overview

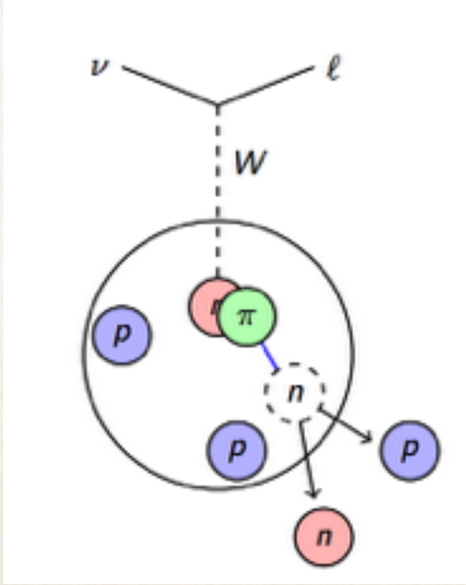
MINERνA's strong suit: provides extensive information about a major source of uncertainty — extension of models from interactions on free nucleons (relatively well understood) to interactions on heavy nuclei:



Impact of nucleus on neutrino interaction
Pauli blocking
multi-nucleon bound states
Fermi momentum



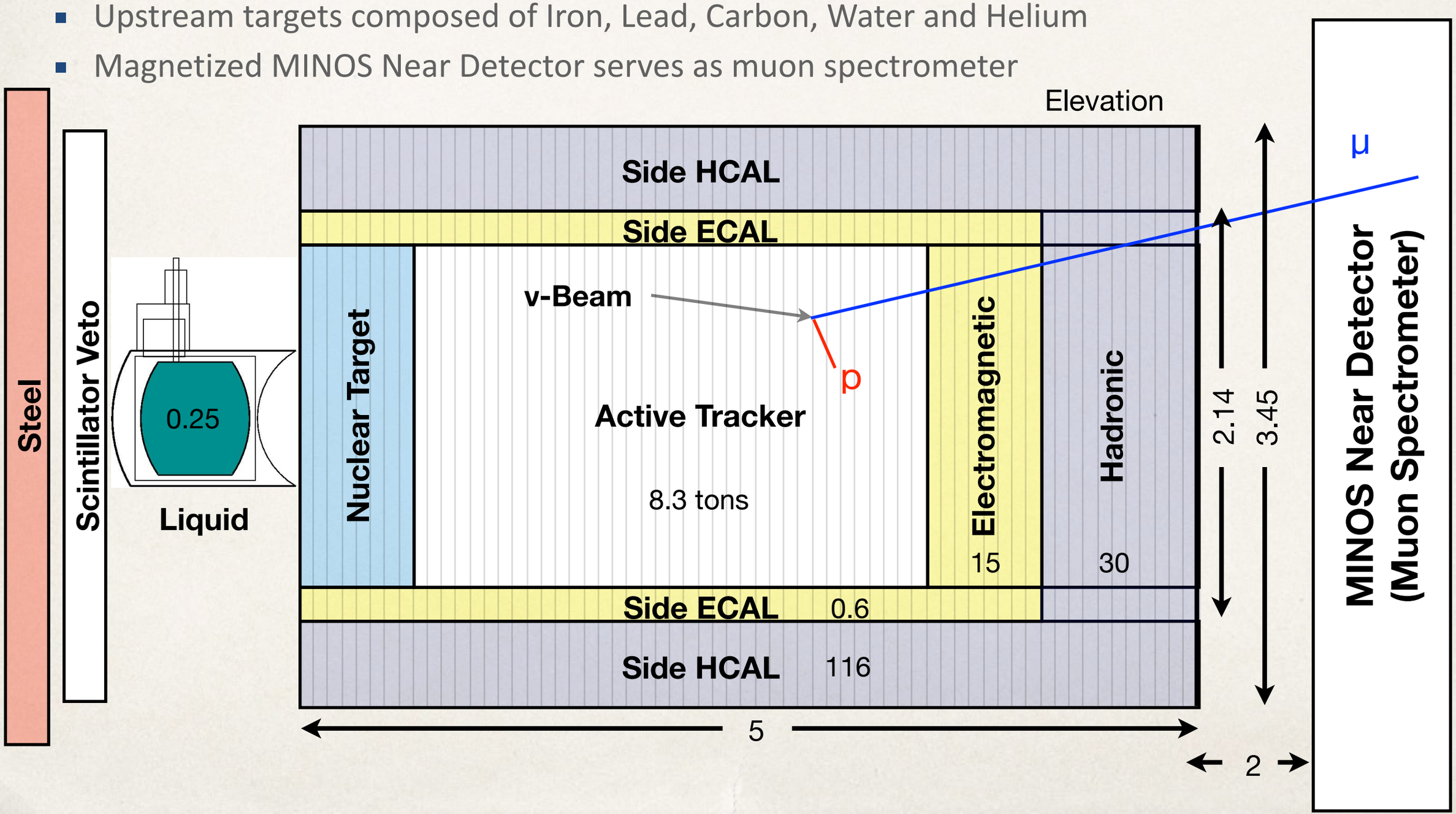
Impact of nucleus on final state kinematics



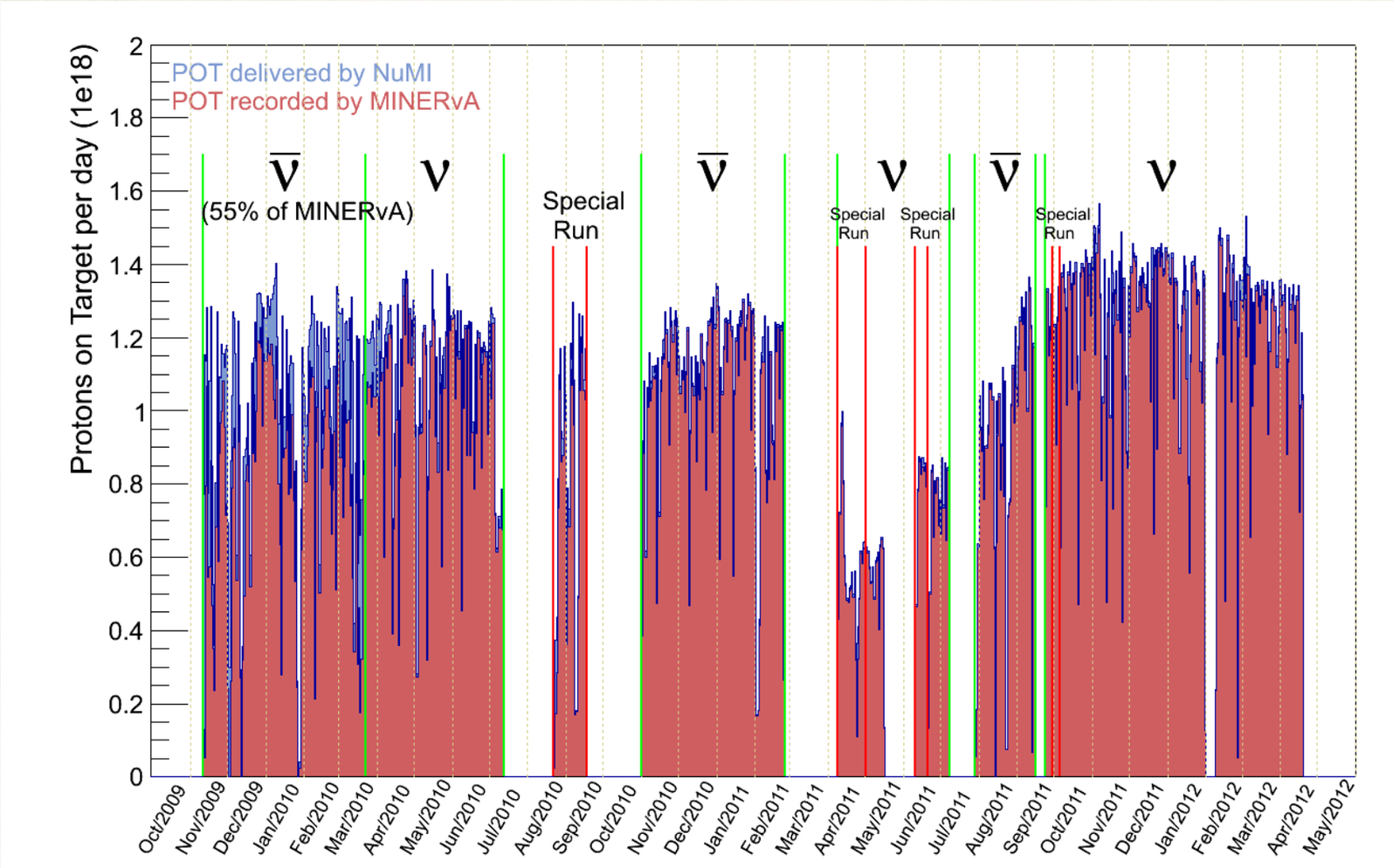
Figures by P. Rodrigues

MINERνA Detector

- Finely segmented detector: ~32k triangular strips of plastic scintillator
  - Active tracker is made completely of scintillator
  - Calorimeters are scintillator + Iron or Lead
- Upstream targets composed of Iron, Lead, Carbon, Water and Helium
- Magnetized MINOS Near Detector serves as muon spectrometer



Accumulated Data

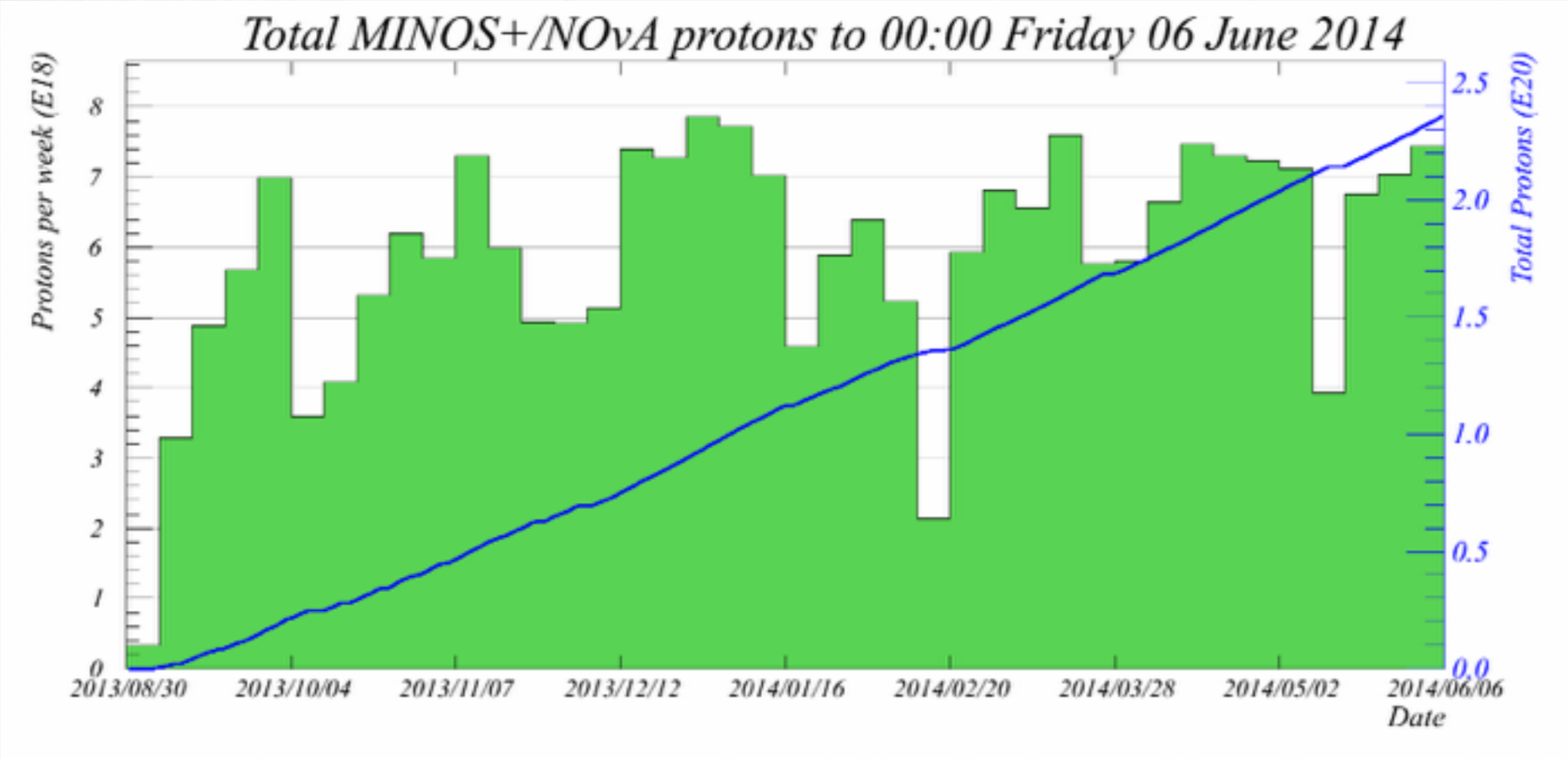


Low Energy Run completed in 2012
3.98e20 POT (ν)
1.7e20 POT ($\bar{\nu}$)

All of the results presented in this talk use this low energy data

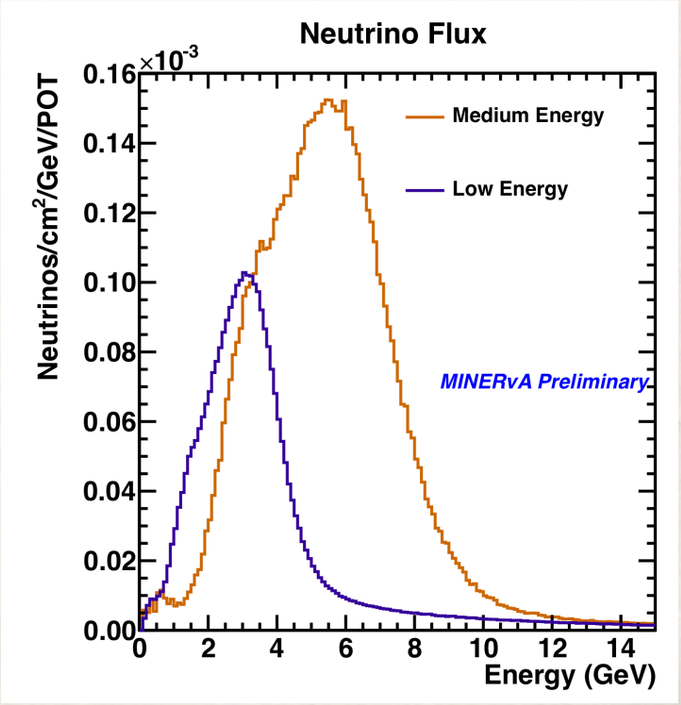
Thank you for the many years of intense beam!

Accumulated Data



Have now accumulated 2.2e20 POT in a higher energy beam, starting Sept 2013

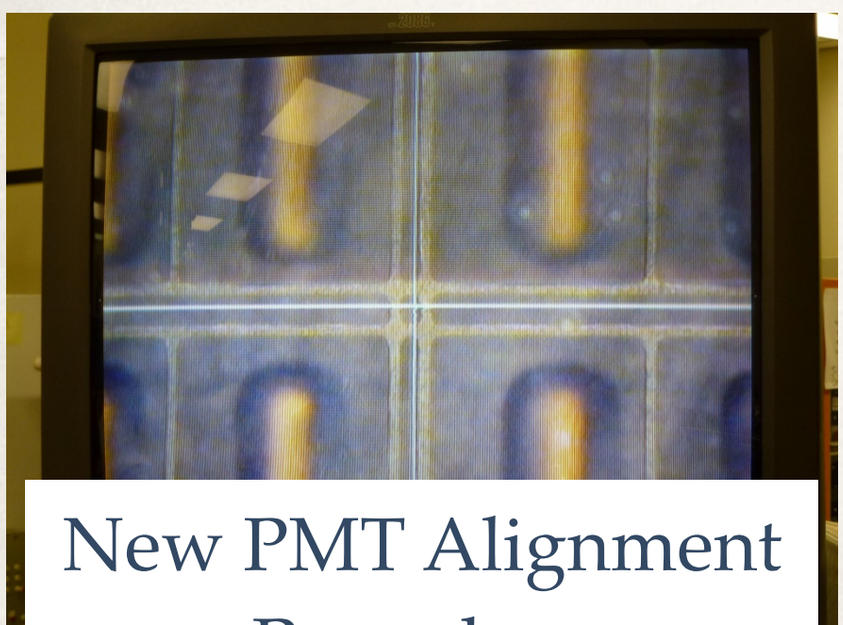
More than half of LE POT already!



- ME data is the best monitored data MINERνA has ever taken (nearly immediate matching with MINOS and beam for high statistics monitoring of through-going muons)
- Experience with LE indicates this sample will be very useful, particularly for statistics limited analyses

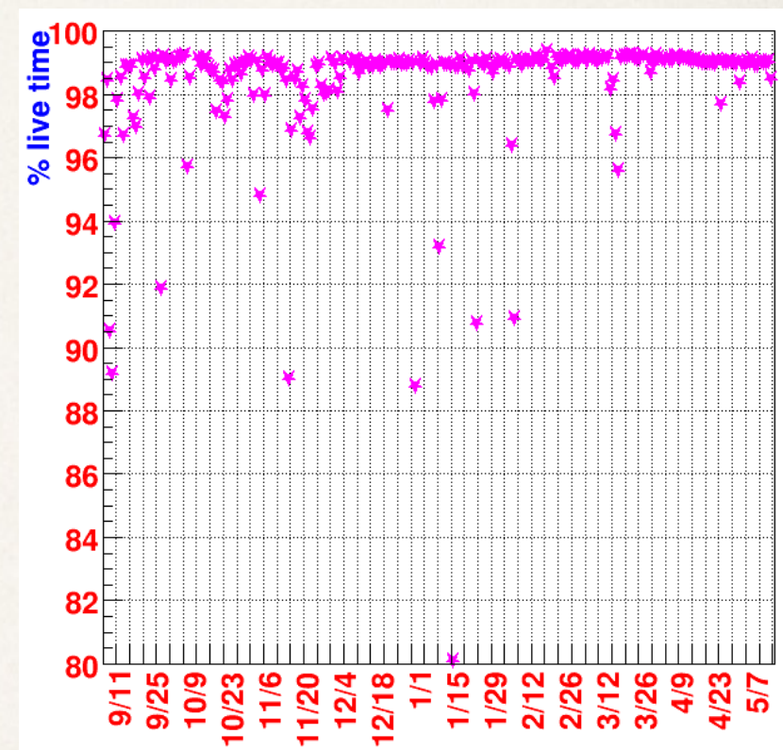
Recent Operations Milestones

Filled He Target



New PMT Alignment Procedure

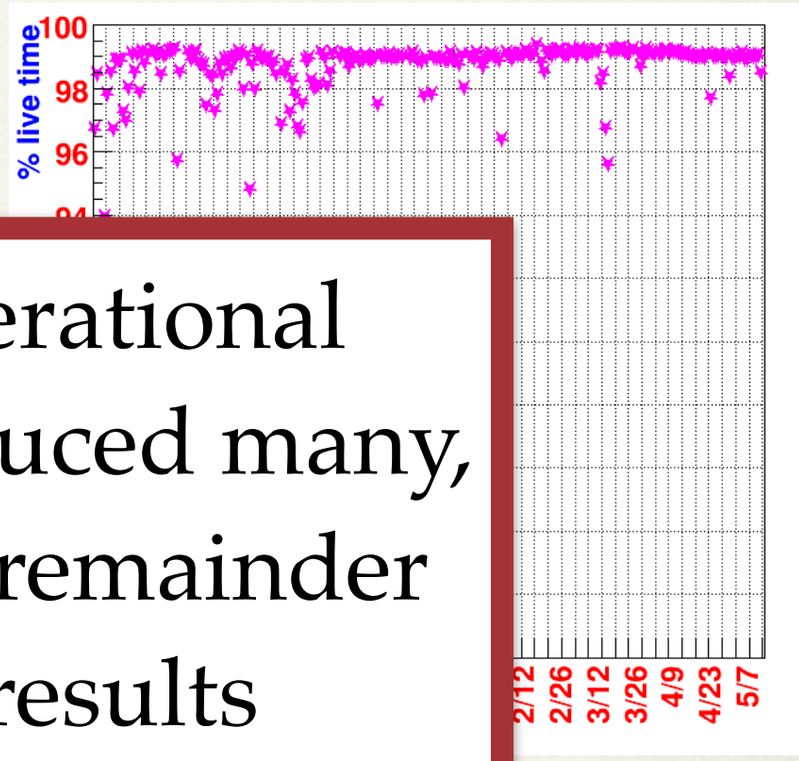
Contributed to installation of 4th NuMI muon monitor



Achieved 97% lifetime

Recent Operations Milestones

Fille



In addition to these many operational milestones, MINERvA also produced many, many new public results. The remainder of this talk discusses those results

New PMT Alignment Procedure

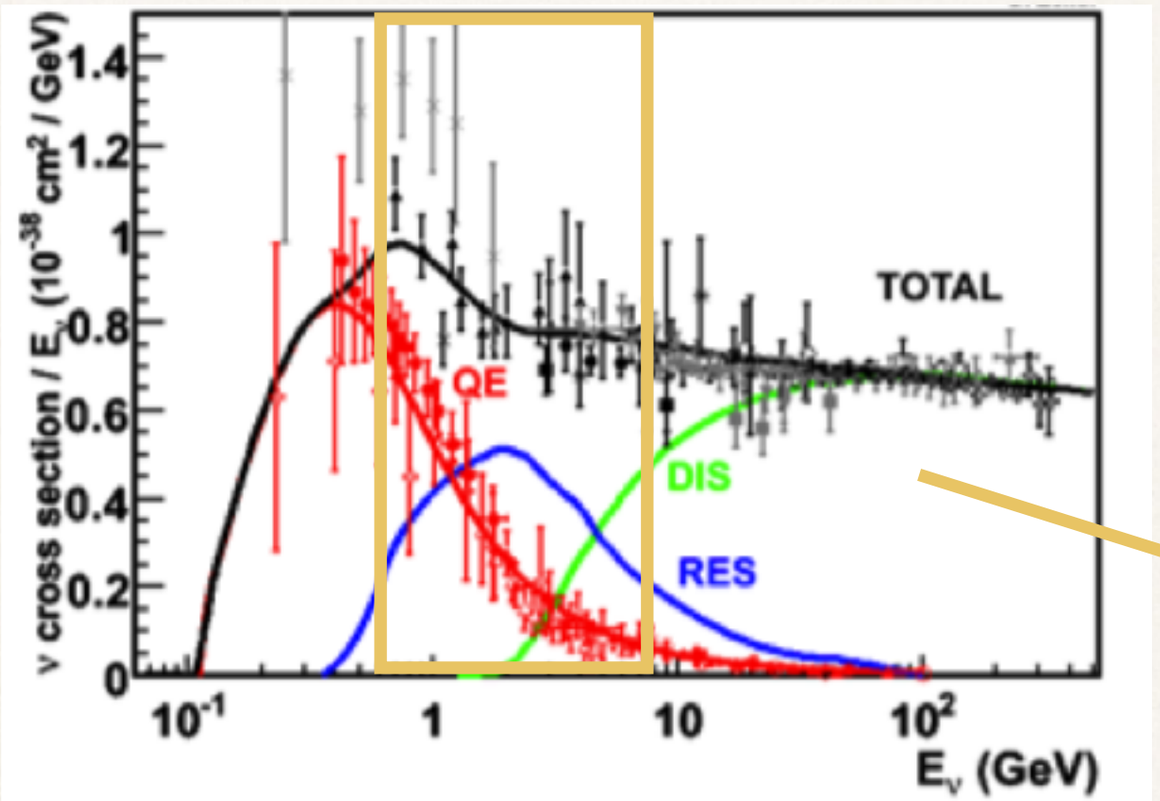
Contributed to installation of 4th NuMI muon monitor

Achieved 97% lifetime

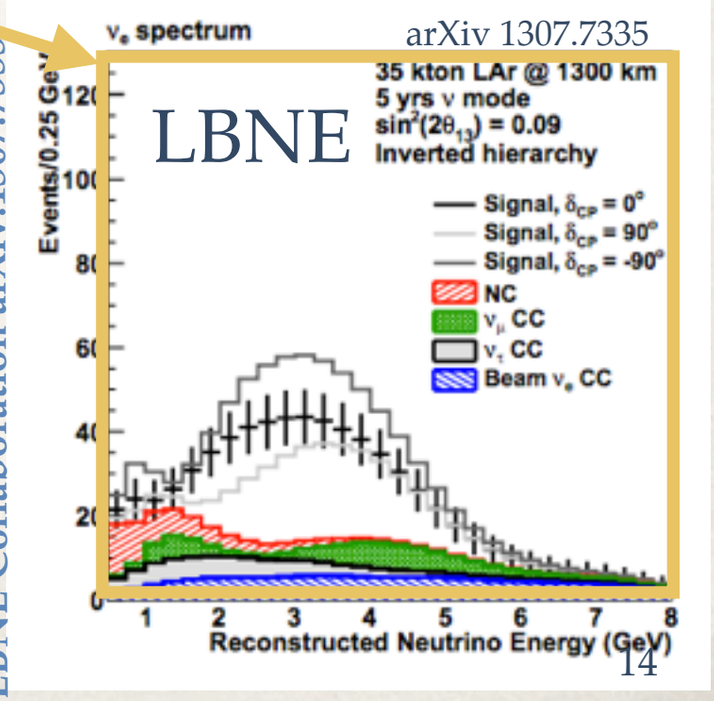
Results — Overview

All of MINERνA's recent results describe *charged current interactions*:

J.A. Formaggio and G.P. Zeller, Rev. Mod. Phys. 84 (2012)



Measurements concentrate on the ~1-10 GeV energy range of interest to long baseline oscillation experiments

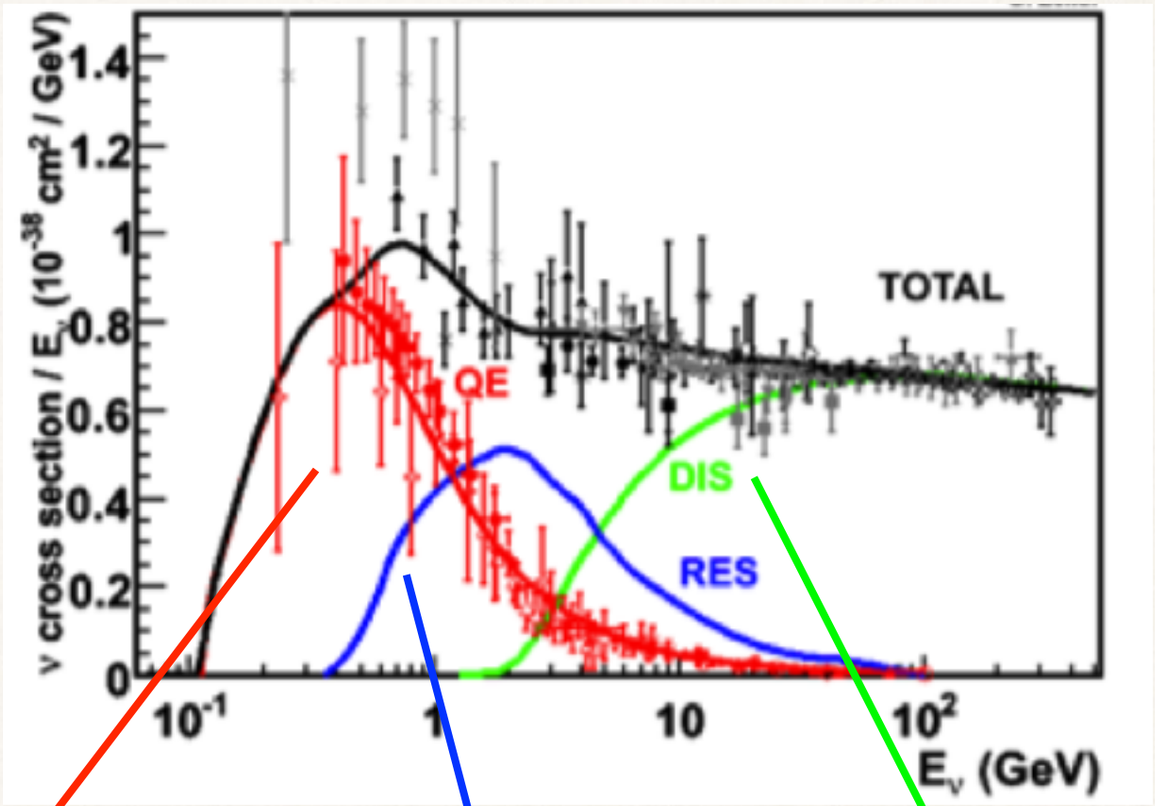


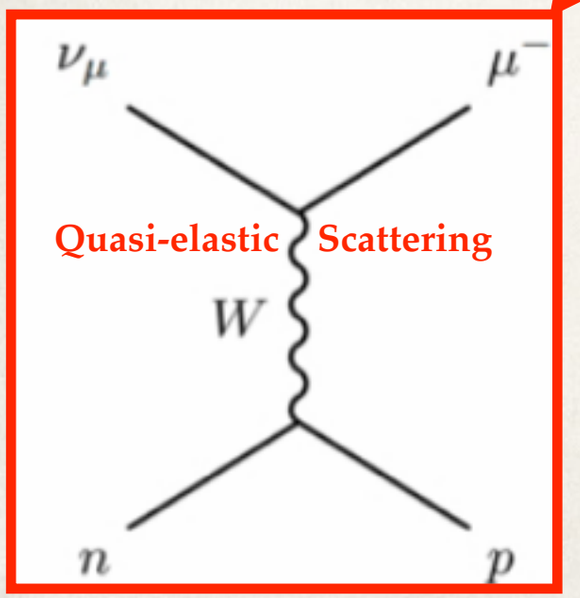
LBNE Collaboration arXiv:1307.7335

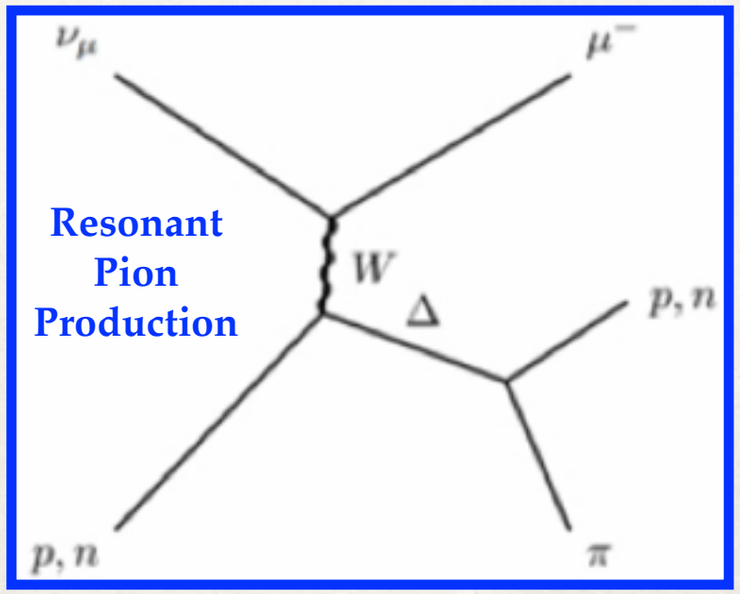
Charged current interactions are the signal and majority of backgrounds in oscillation measurements arise from charged current interactions

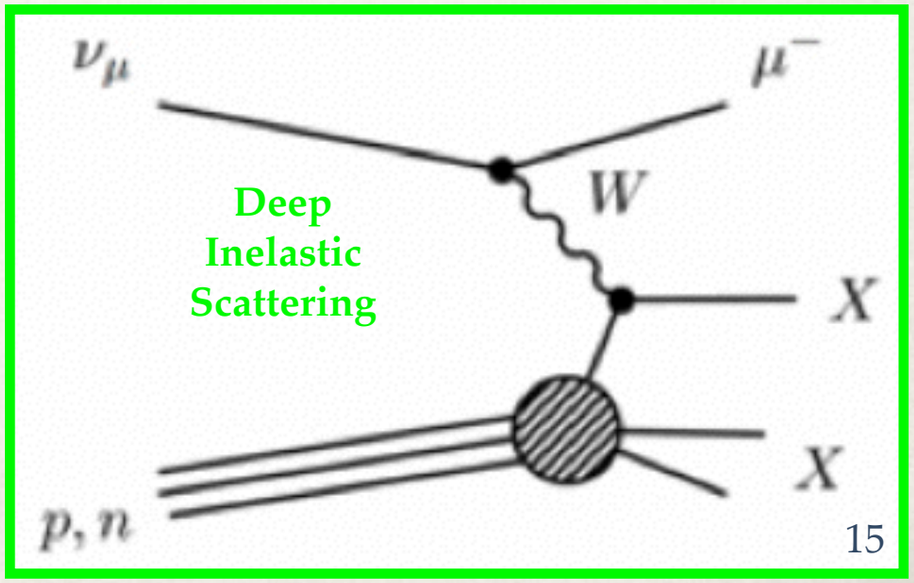
Results — Overview

J.A. Formaggio and G.P. Zeller, Rev. Mod. Phys. 84 (2012)









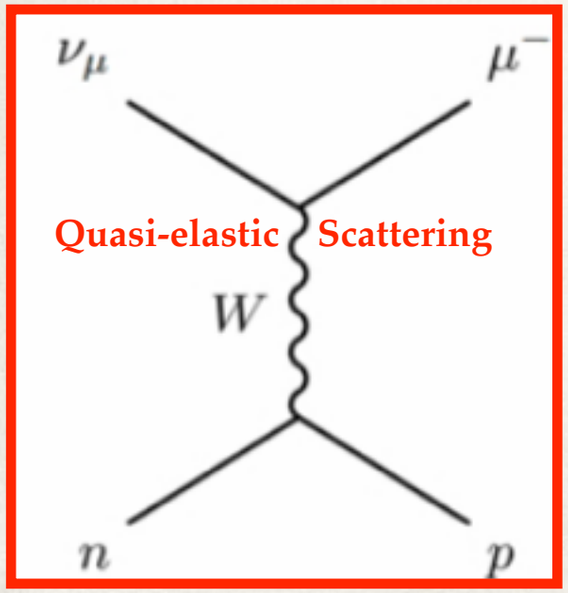
Results — Overview

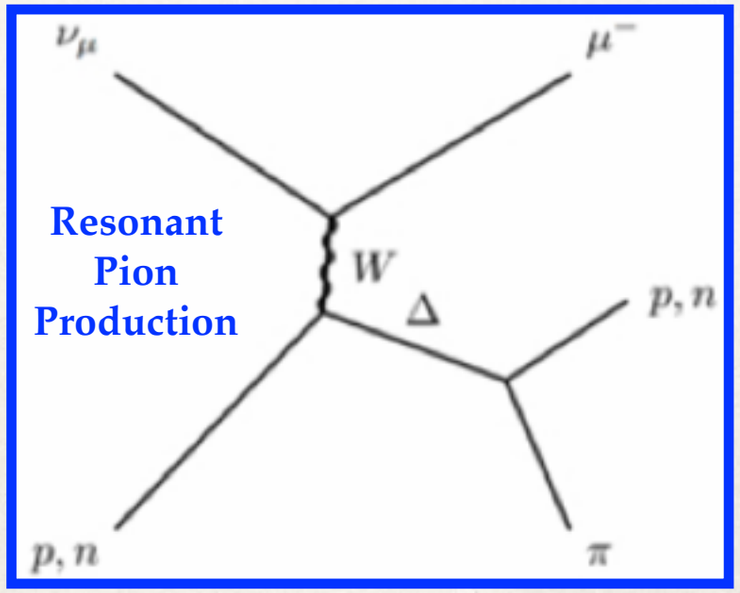
Results I'll be discussing today:

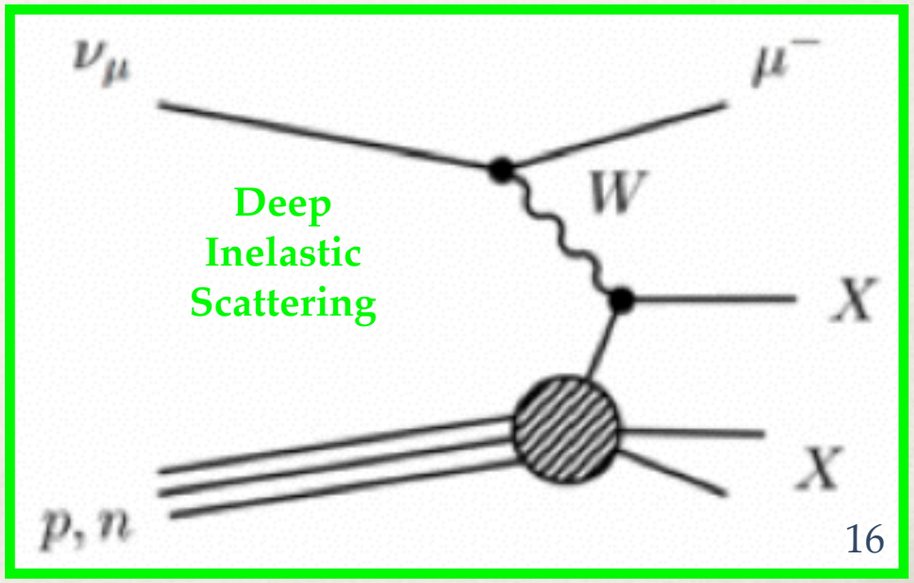
Two analyses that study quasi-elastic scattering (one minimally sensitive to FSI and one that directly probes FSI)

Two analyses that probe pion production (again, one sensitive to FSI and one not)

One analysis that looks at all three modes together across different nuclei







Results: Overview

But first: an important ingredient in all of these results:

Unfolding Matrix — Events Observed — Background Estimate

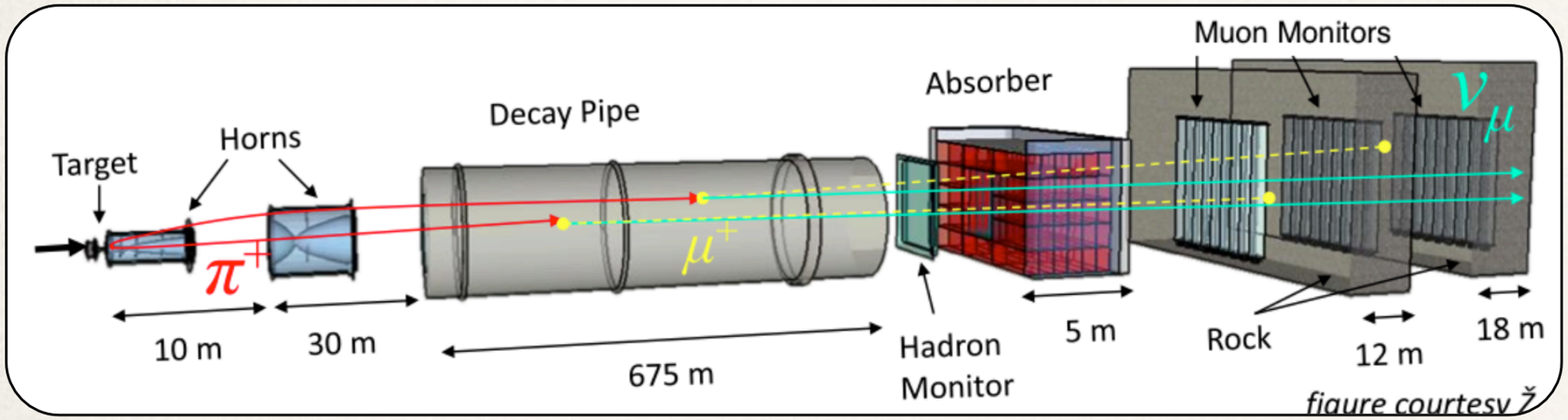
$$\sigma_i = \frac{U_{ij}(N_j - B_j)}{\Phi_i T \varepsilon_i}$$

Nucleons in Detector — Efficiency

Flux

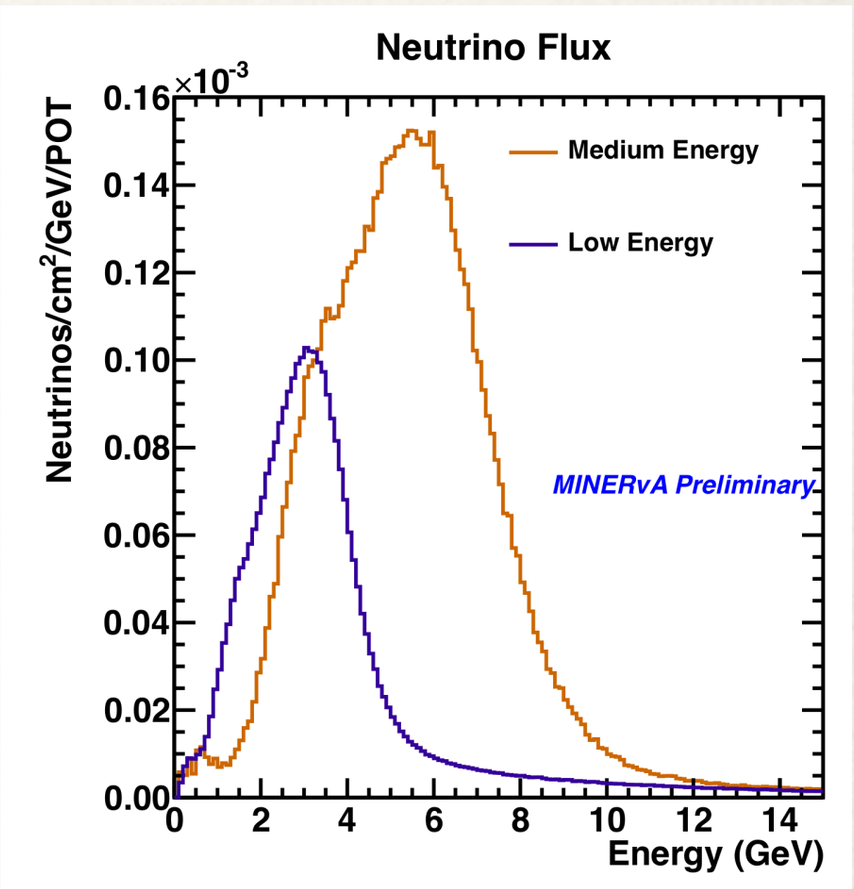
= Number of neutrinos in beam as a function of energy

Results: Flux

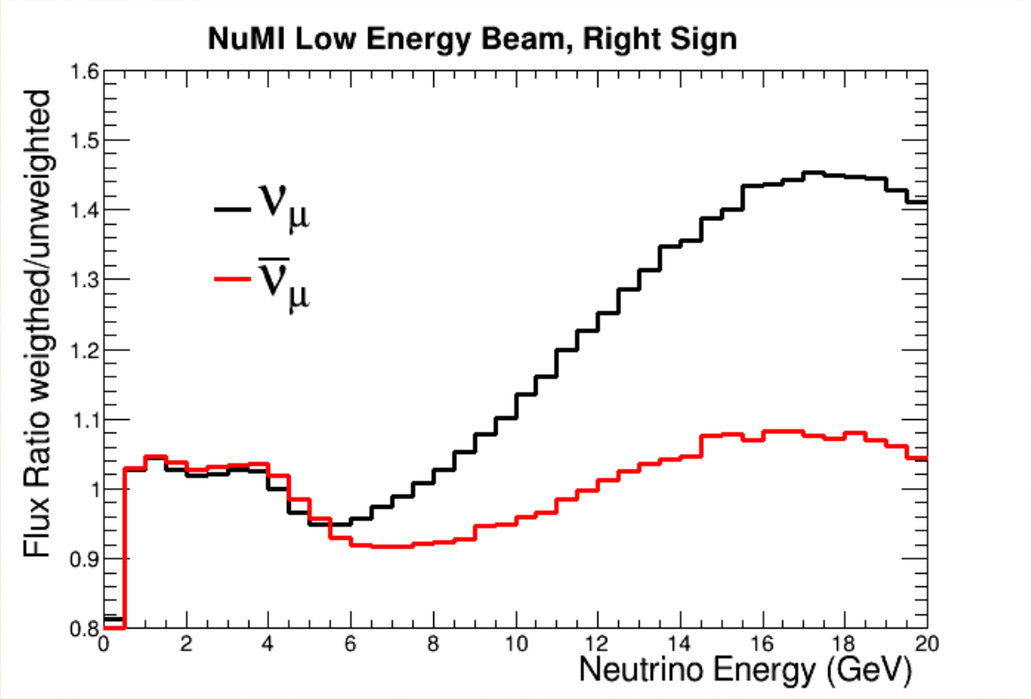


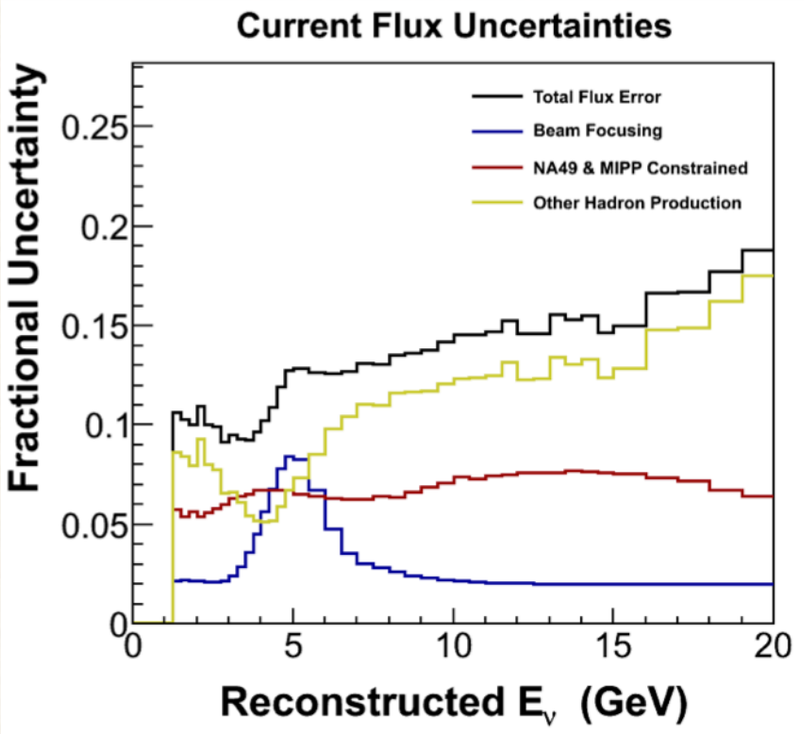
MINERνA

- Flux estimate starts with a Geant4-based simulation of the NuMI beam line



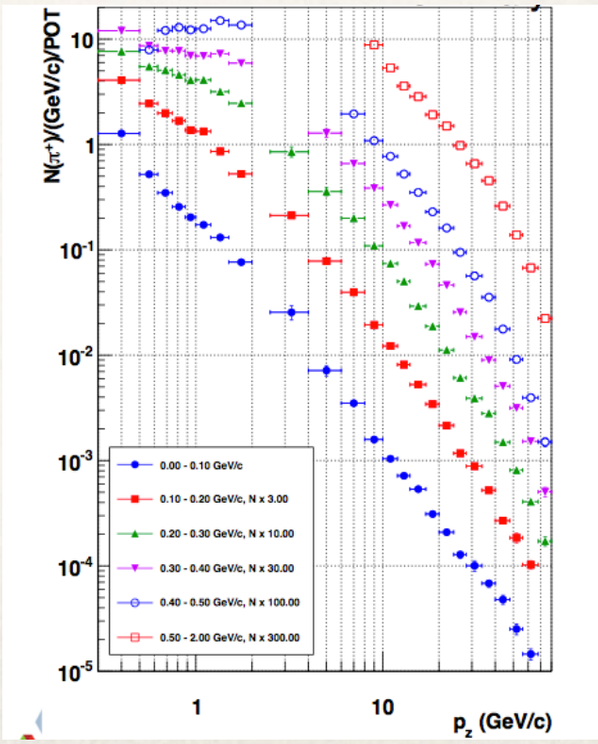
Results: Flux





- Geant4 model constrained by NA49 and MIPP (pi/k ratio only); current flux has ~10% uncertainties in focusing peak

- Currently working to incorporate MIPP's latest hadron yield results



Ref: J.M.Paley, M.D.Messier, R.Raja et al, arXiv: 1404.5882

Flux: ν - e Scattering

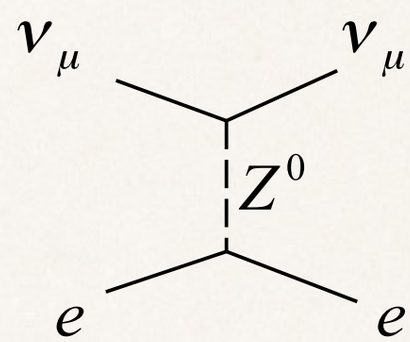
- We are also pursuing several in situ flux constraints:

  - Neutrino scattering on electrons is another well understood standard candle

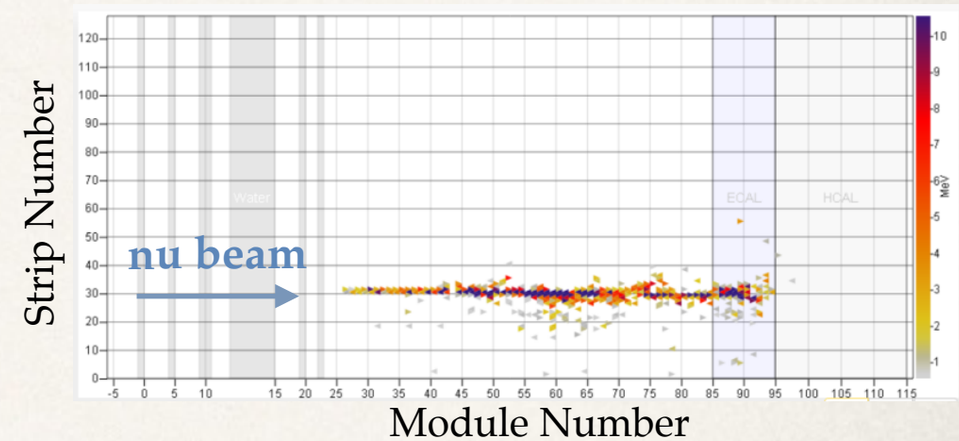
  - Signal in MINERνA is a single electron moving in beam direction

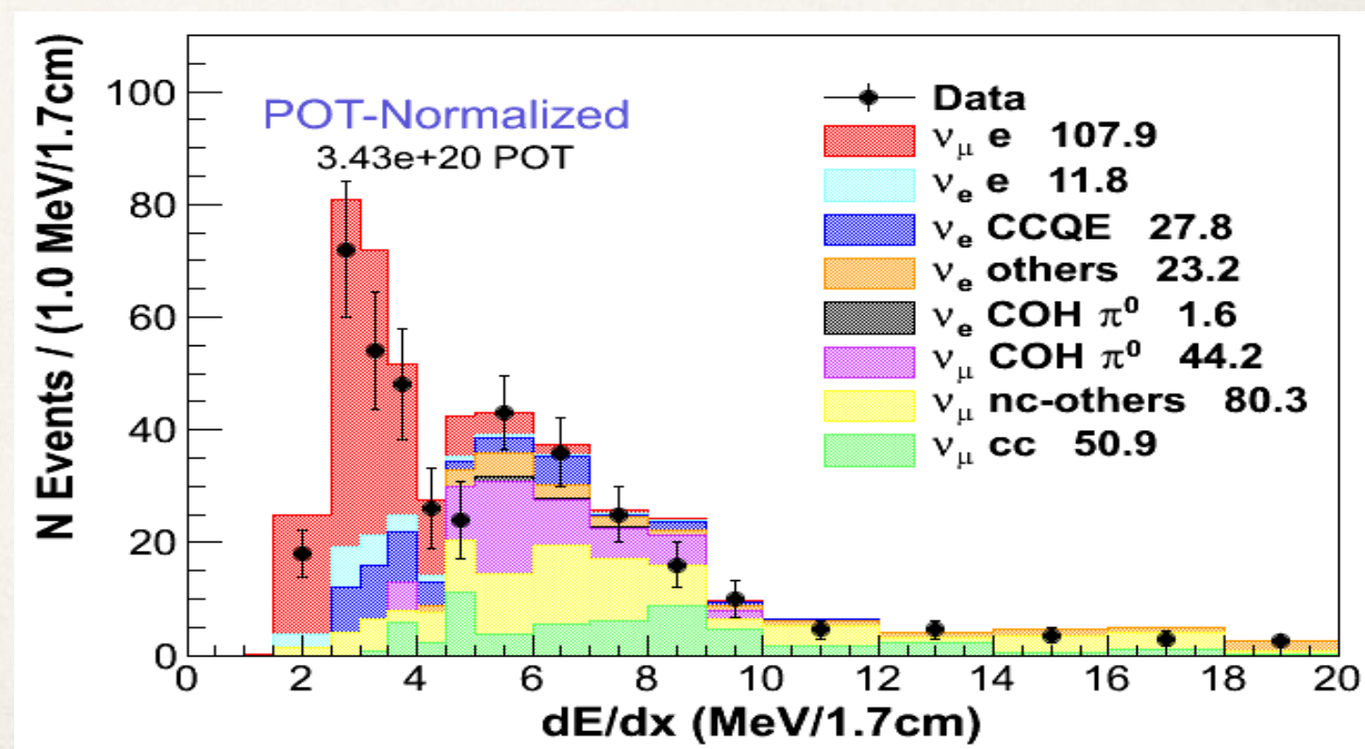
  - Process cross section is smaller than nucleus scattering by a factor of 2000→ statistically limited

  - Will improve MINERνA's flux uncertainties (esp medium energy beam) and be an important proof of principle for future experiments



MINERνA Data

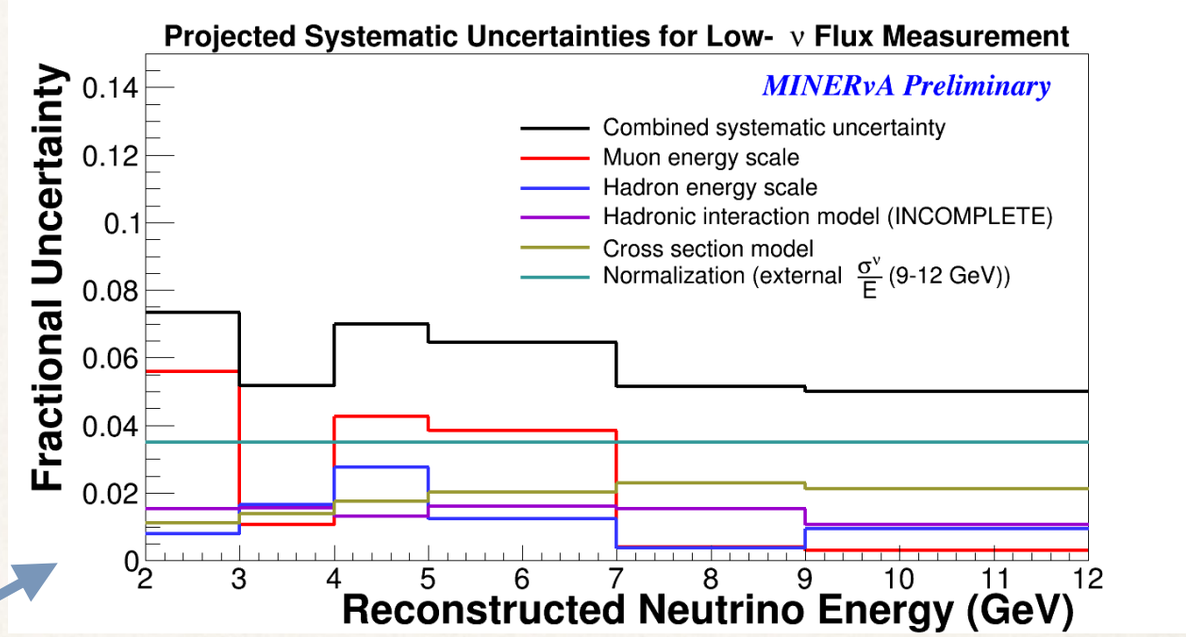


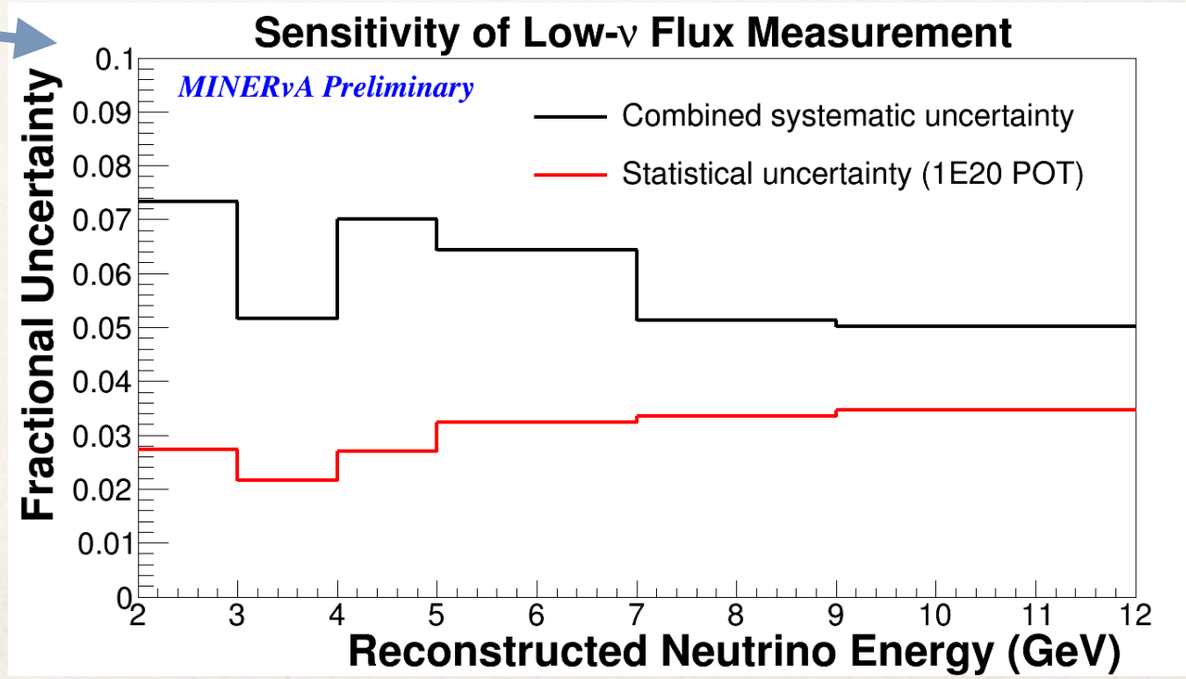


Flux: Low ν

- We are also pursuing several in situ flux constraints:
  - Charged-current scattering with lower hadronic recoil energy (ν) is another standard candle
  - Gives a good measurement of flux shape; normalization tied to external measurements at high energy
  - No results yet, but preliminary estimates of systematic uncertainty are promising

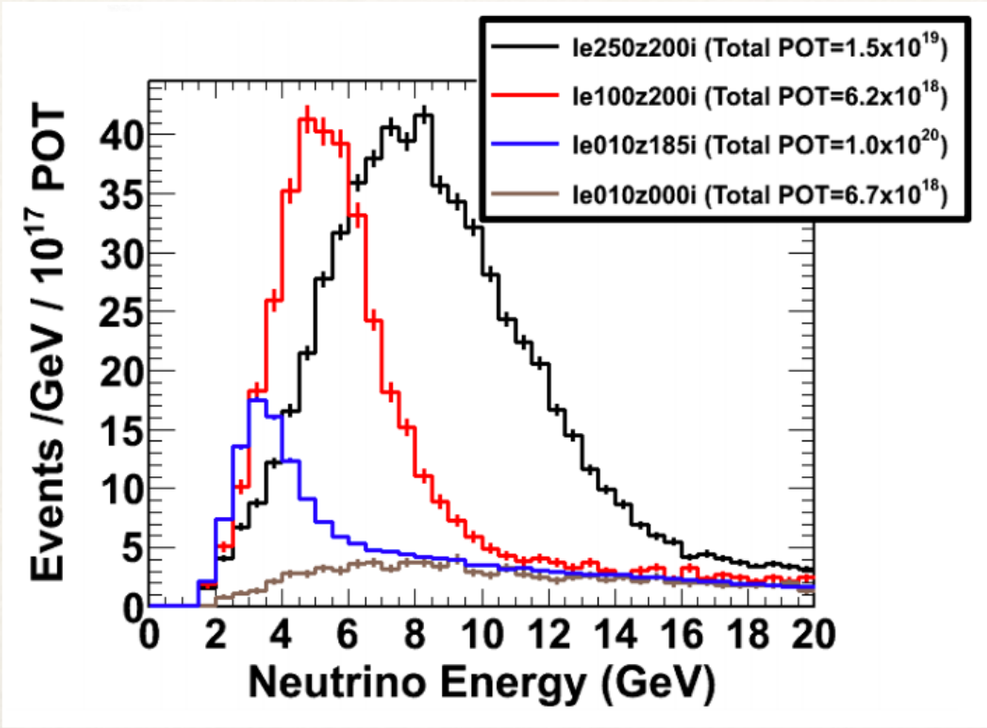
$$\frac{d\sigma}{d\nu} = A(1 + \frac{B}{A}\frac{\nu}{E} - \frac{C}{A}\frac{\nu^2}{2E^2})$$



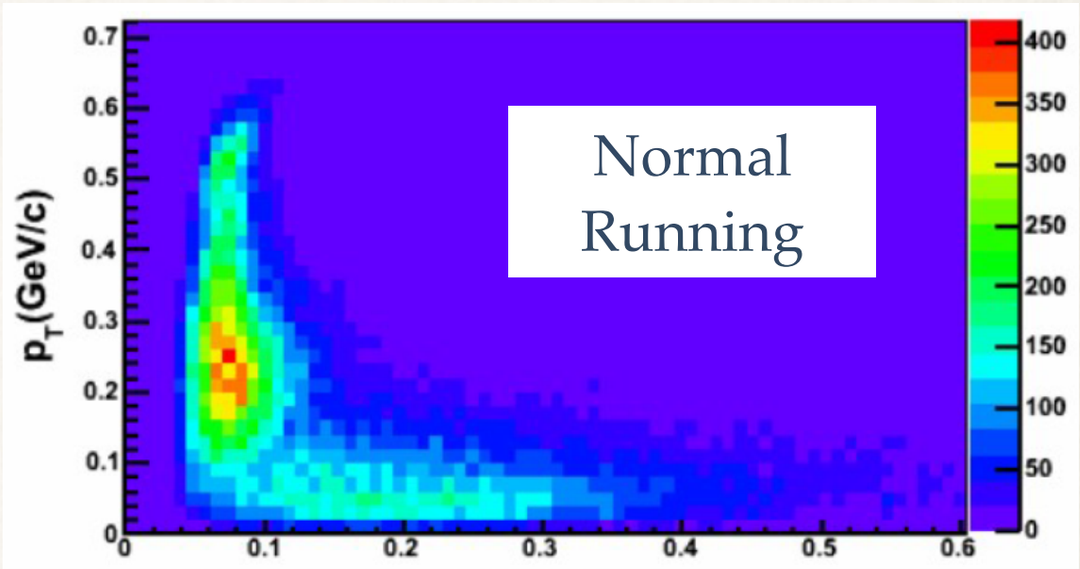


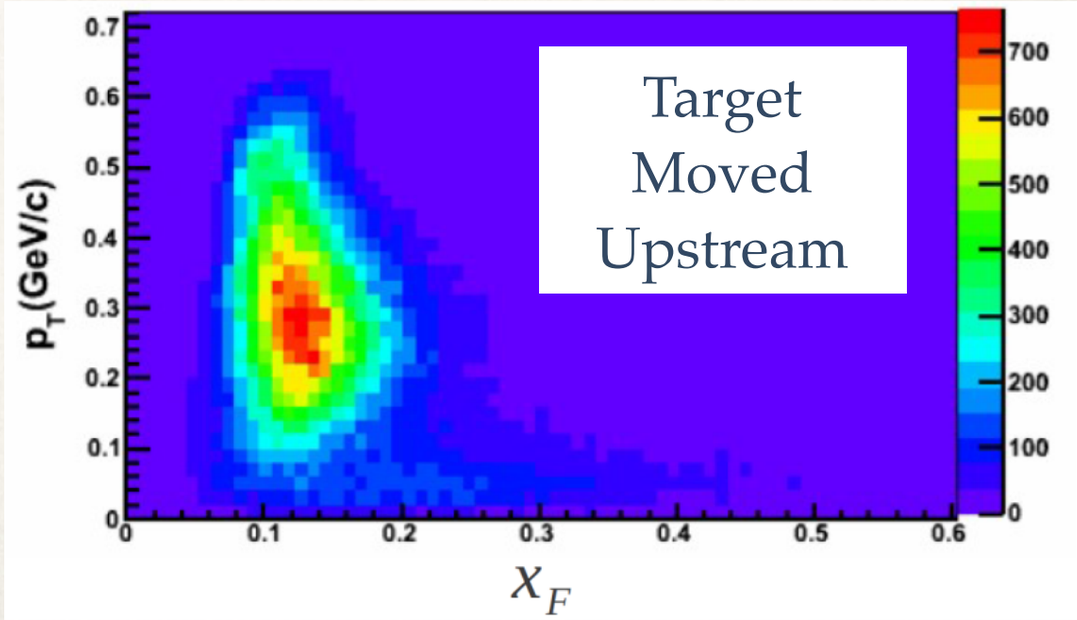
Flux: Special Runs

- We are also pursuing several in situ flux constraints:
  - Can also utilize "special runs" data taken with various target positions and horn currents
  - Disentangles focusing uncertainties from hadron production uncertainties



Pions that produce neutrinos in MINERvA





Results: Overview

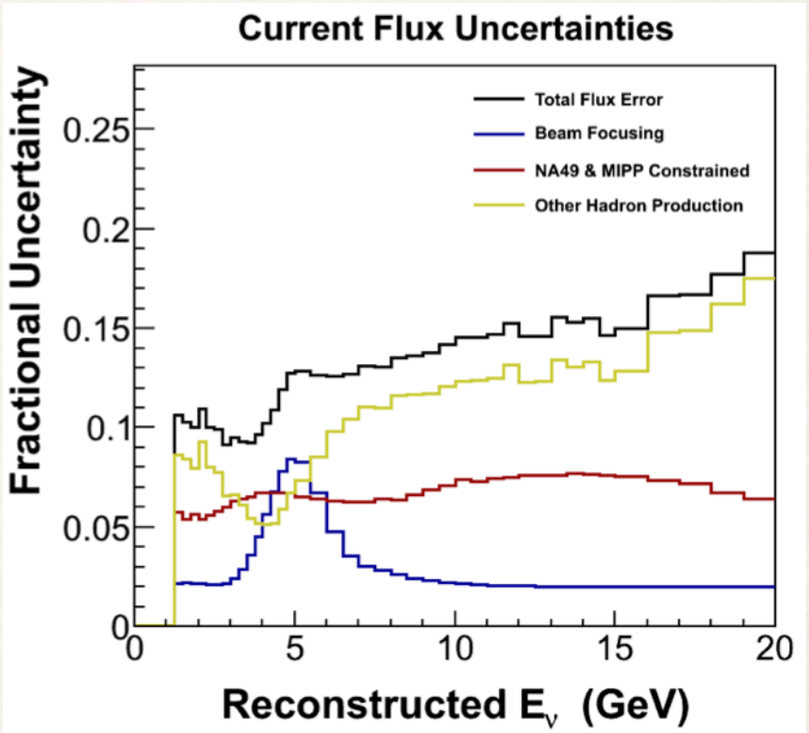
Let's now turn to cross section measurements that use our current flux prediction (based on GEANT4, NA49 + MIPP pi/k ratio), which leads to ~10% normalization uncertainties

Unfolding Matrix — Events Observed — Background Estimate

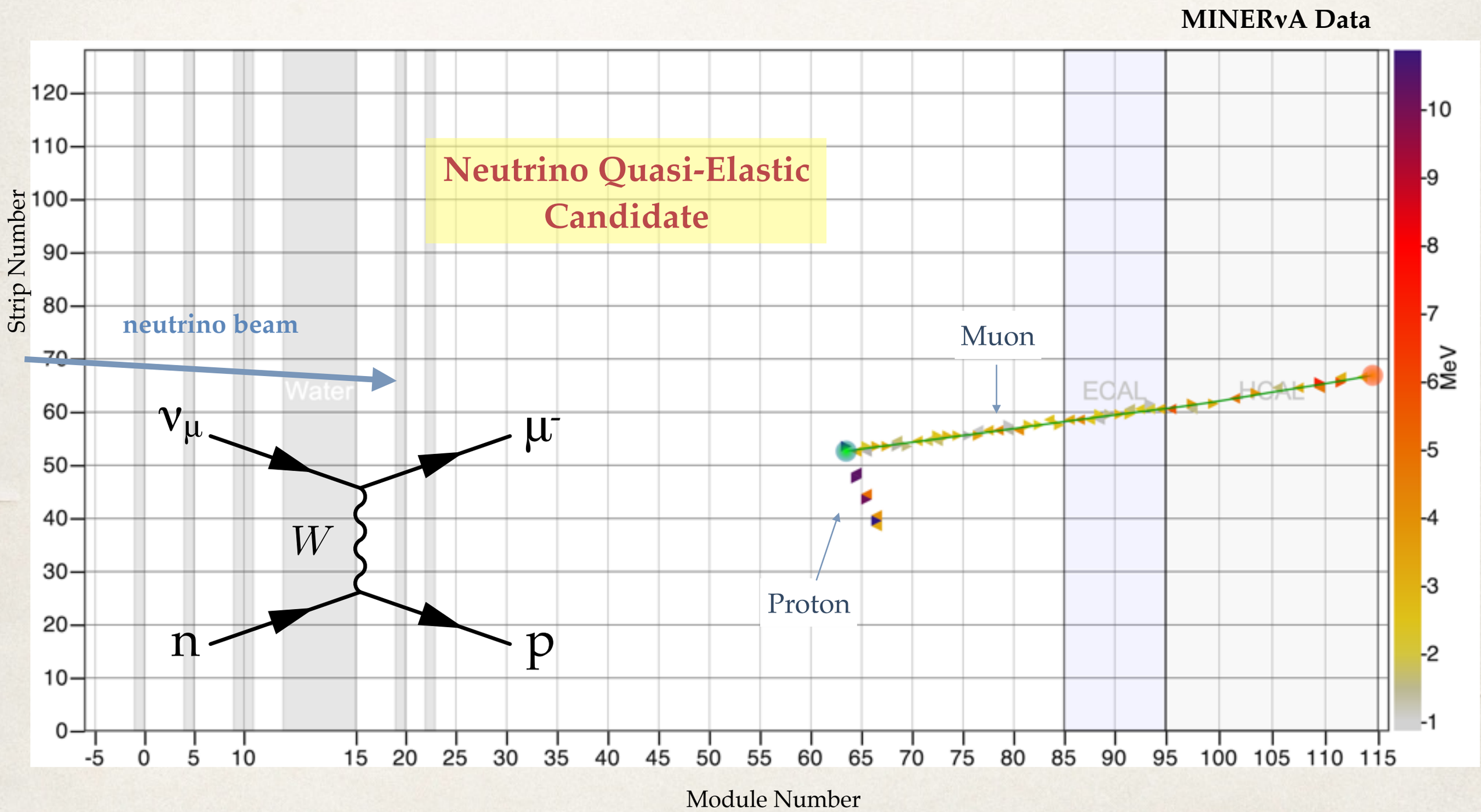
$$\sigma_i = \frac{U_{ij}(N_j - B_j)}{\Phi_i T \varepsilon_i}$$

Nucleons in Detector — Efficiency

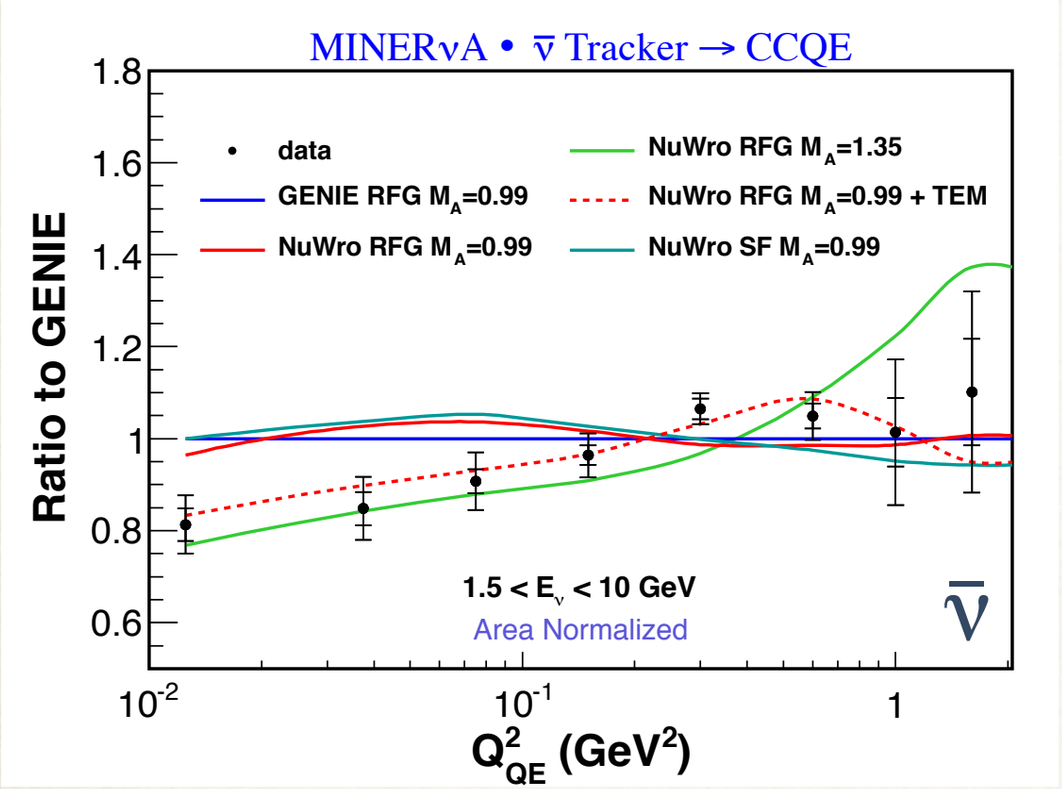
Flux



Results: Quasi-Elastic Scattering



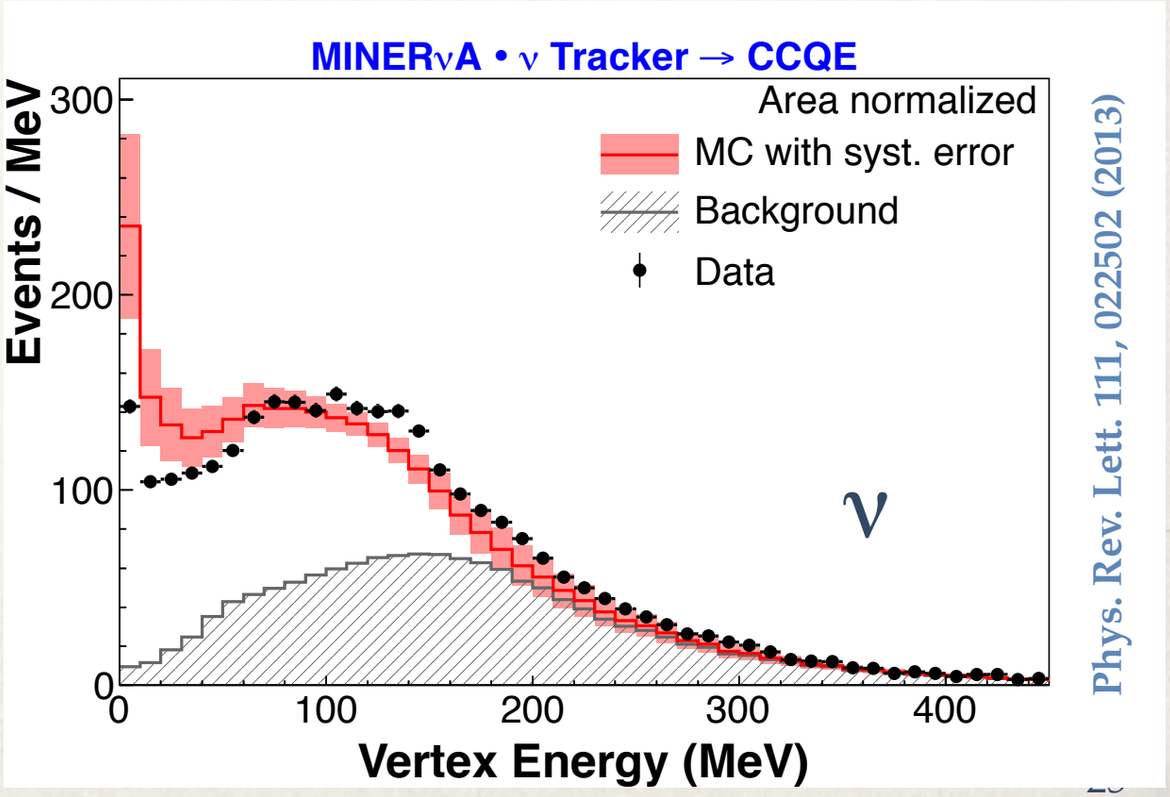
Results: Quasi-Elastic Scattering



Phys. Rev. Lett. 111, 022501 (2013)

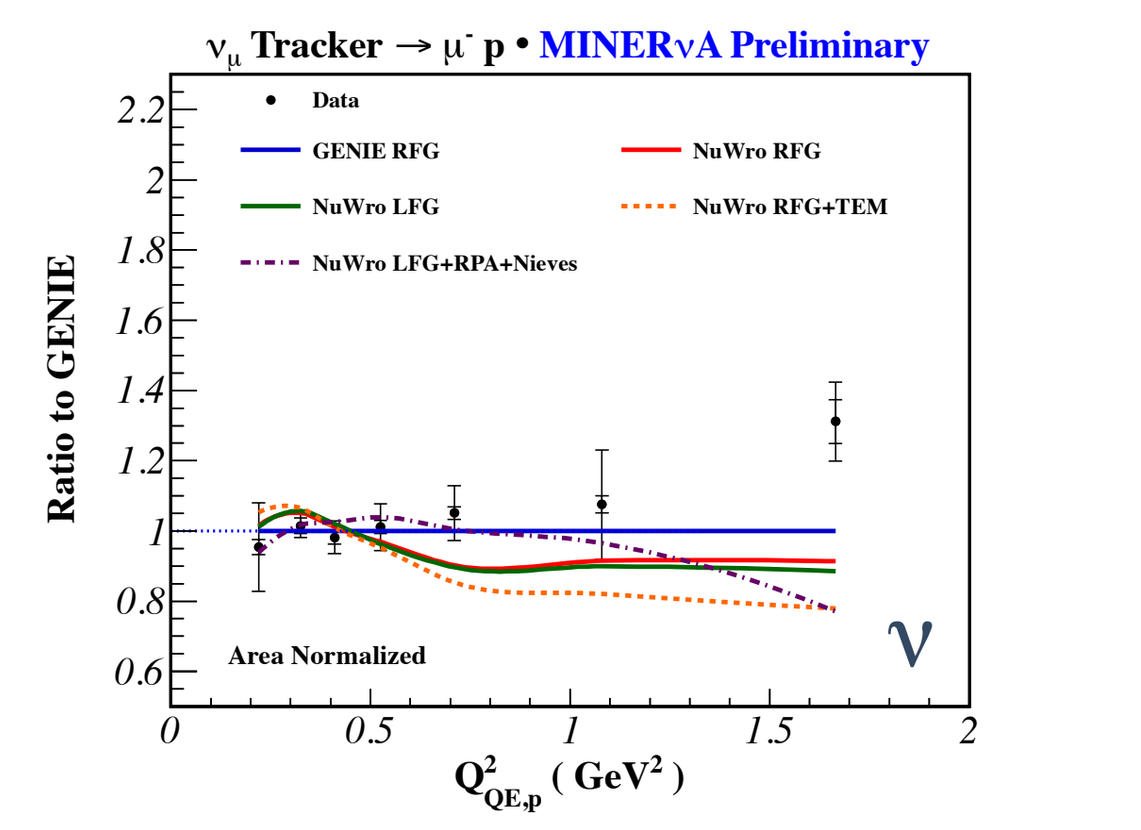
- Disagreement with conventional model seen in total cross section, shape of cross section and amount of activity near the vertex
- Mismatch of vertex energy indicates models underestimate energy of hadronic systems, which will cause biases in neutrino energy reconstruction in oscillation measurements.

- Our first Quasi-elastic analysis reconstructs only the muon
- Relatively insensitive to final state interactions (which enter only in background estimate)



Phys. Rev. Lett. 111, 022502 (2013)

Results: Quasi-Elastic Scattering



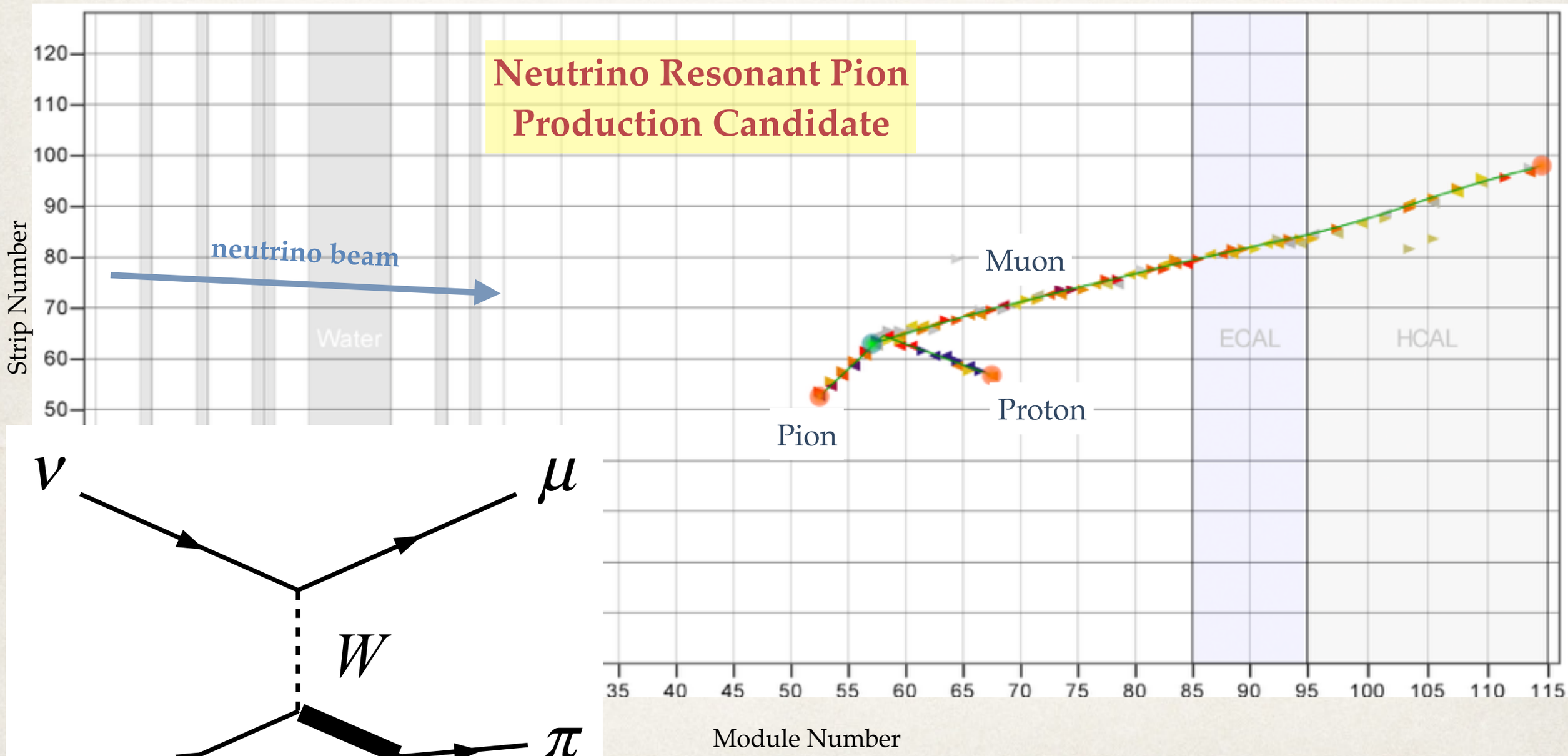
See T. Walton Wine & Cheese, 9 May 2014

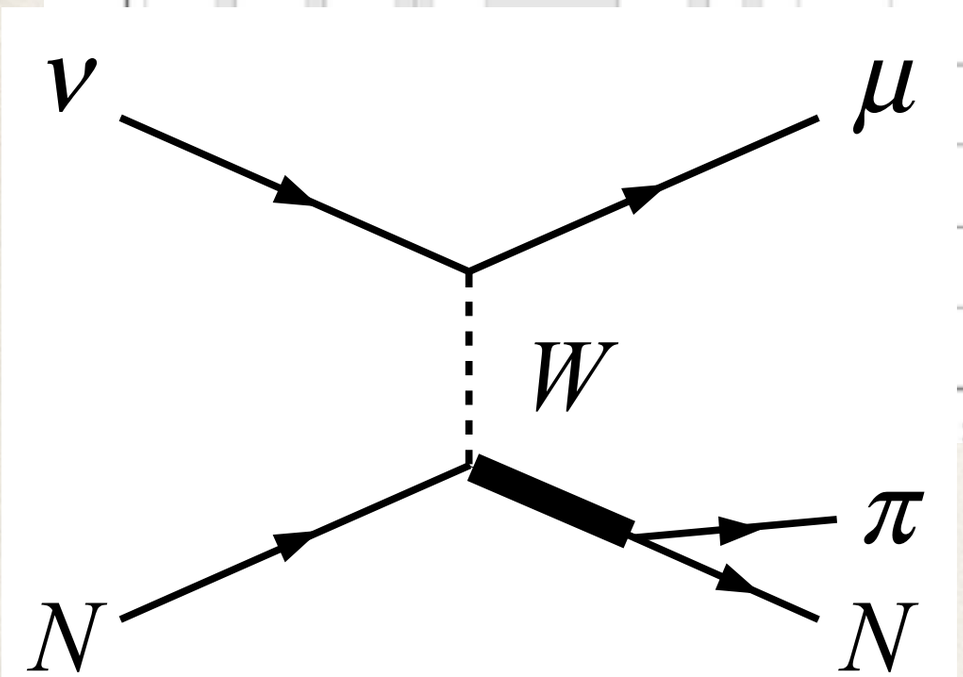
- Newest quasi-elastic measurement reconstructs kinematic quantities using the proton rather the muon
- Very sensitive to final state interactions
- First MINERvA charged-current analysis that uses non MINOS-matched tracks

- In proton kinematic variables, see relatively good agreement with conventional model of QE scattering
- Models that describe the muon do not necessarily get the proton (and it's final state interactions right) — we need a model that gets *everything* right

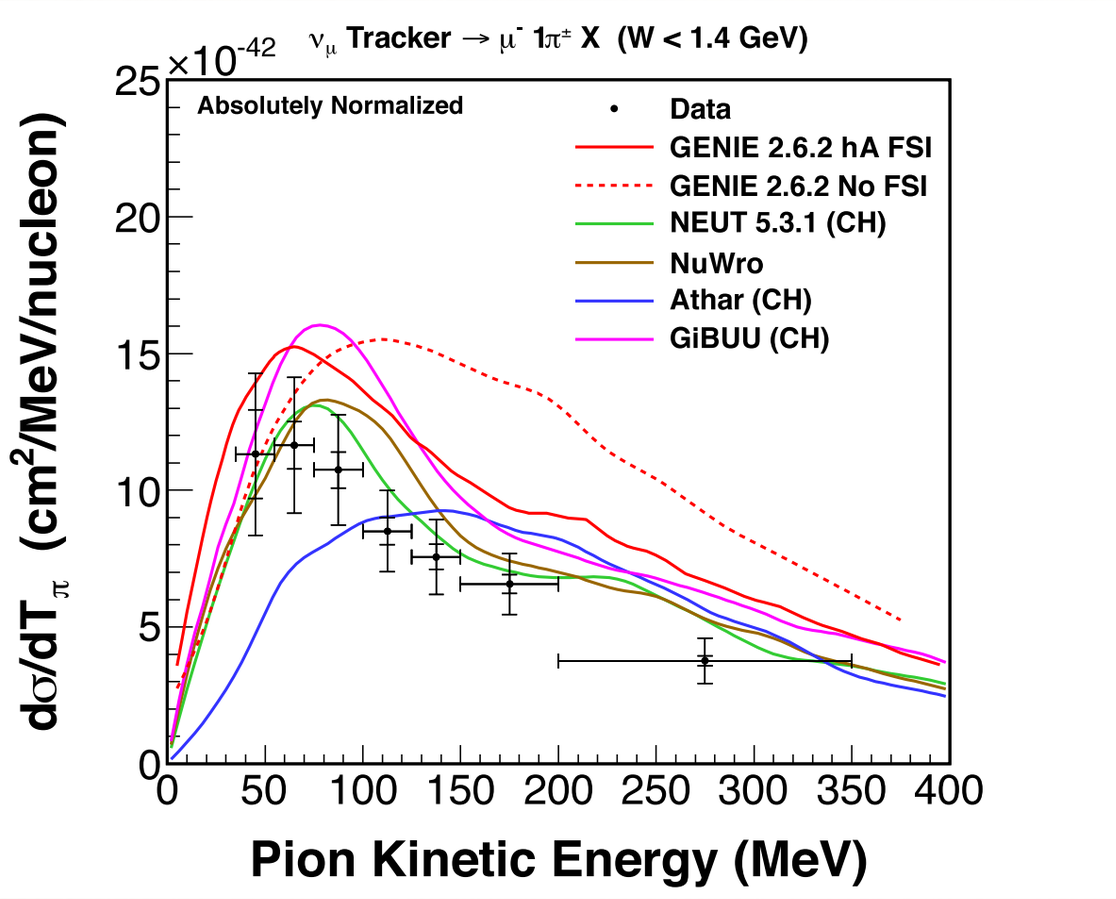
Results: Resonant Pion Production

MINERνA Data

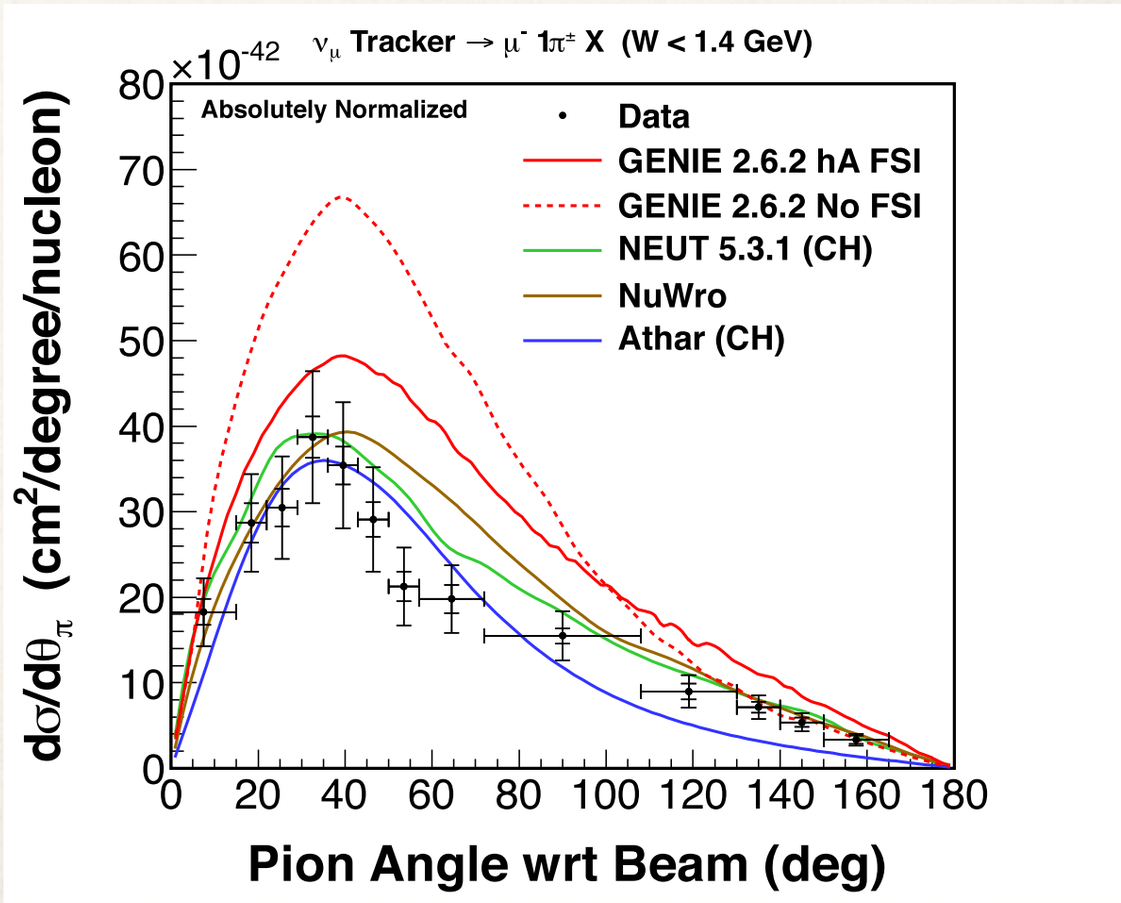




Results: Resonant Pion Production

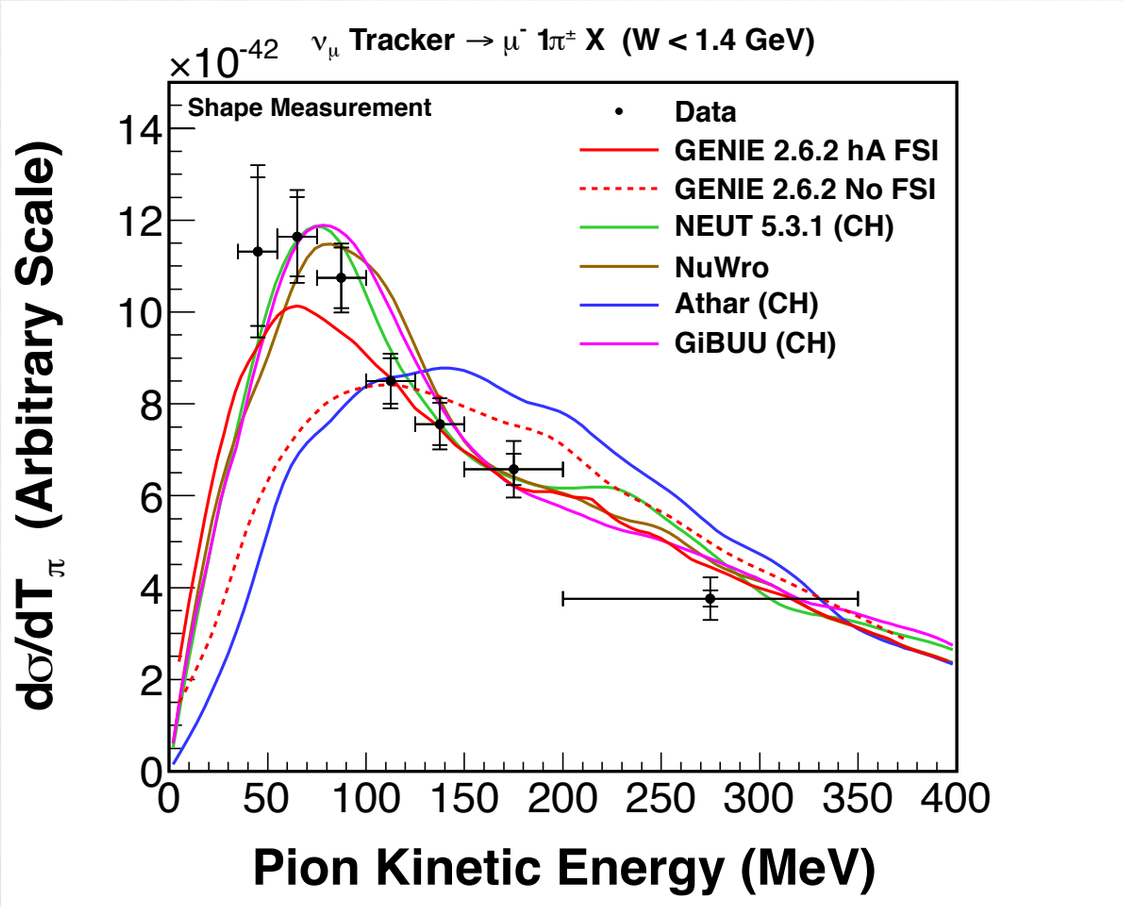


- MINERvA has measured differential cross sections with respect to the energy and angle of the pion

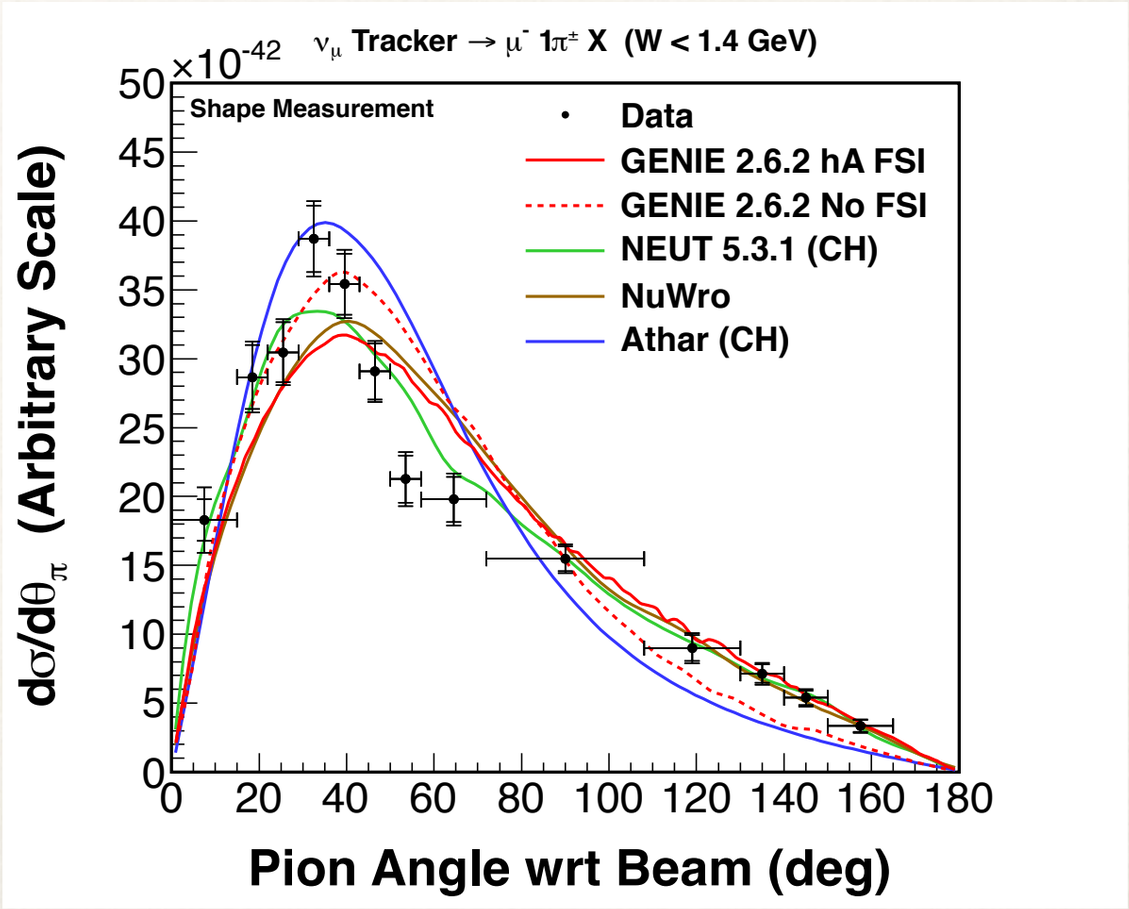


- Both shape and absolute normalization of most models that include modern implementations of final state interactions agree with data; GENIE modestly overpredicts rate

Results: Resonant Pion Production



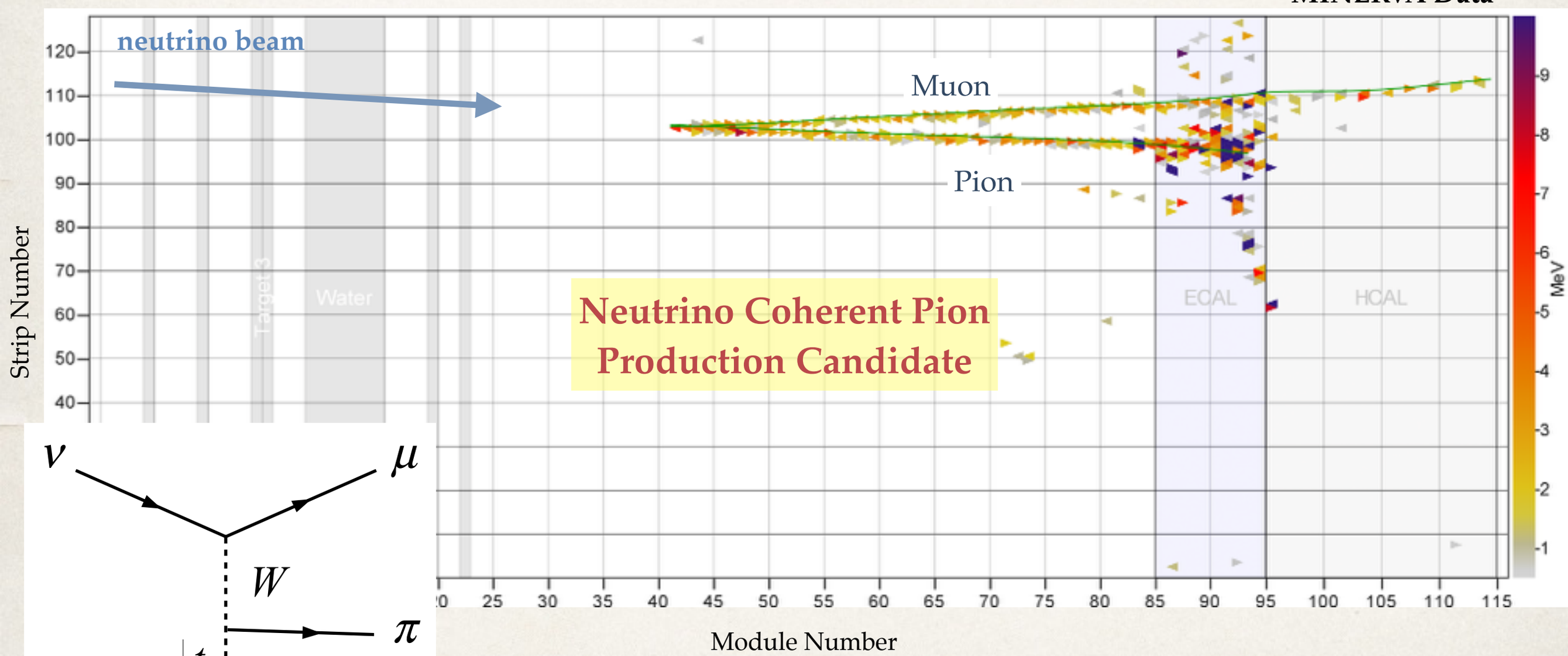
- See B. Eberly Wine & Cheese Feb 7 2014
- Paper with these results is in preparation now

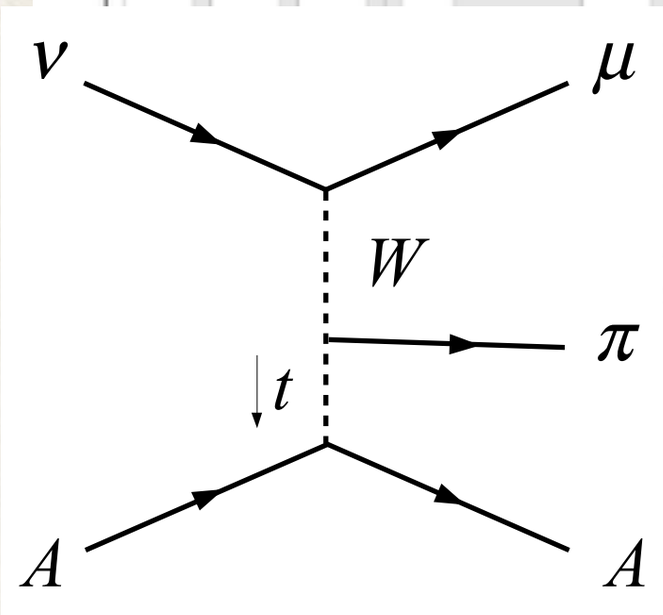


- Further mining of this data sample via study of muon kinematics is also underway

Results: Coherent Pion Production

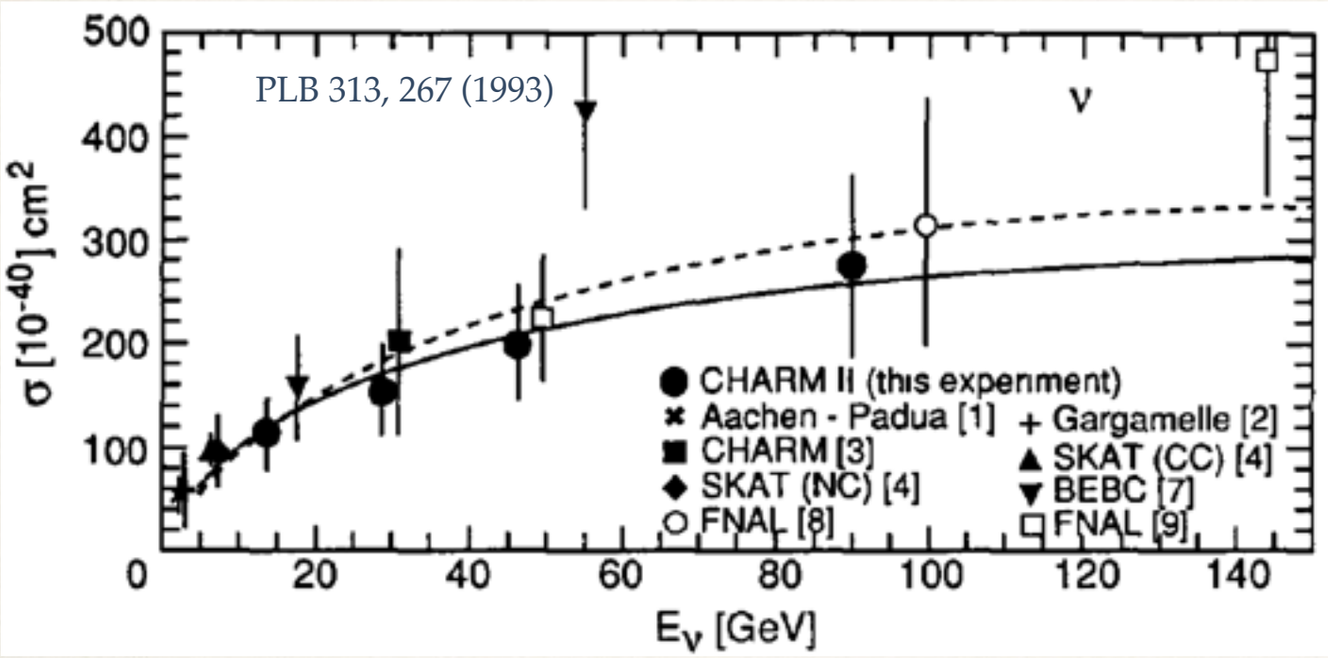
MINERνA Data



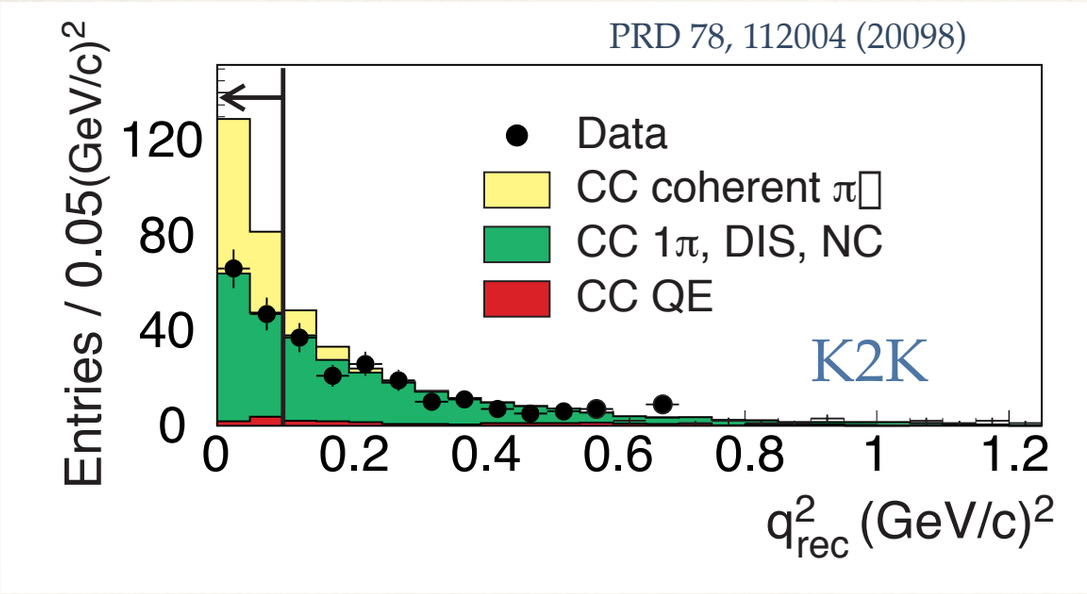


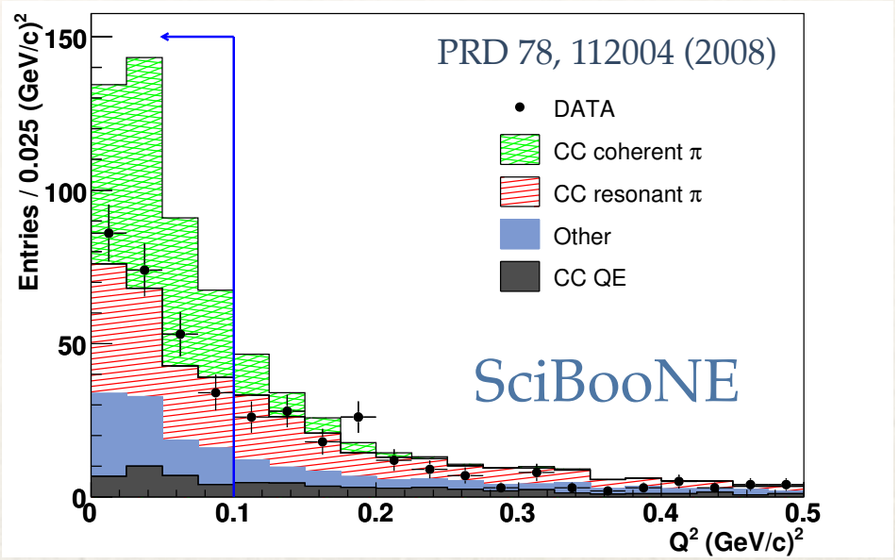
Results: Coherent Pion Production

- Some coherent pion history:

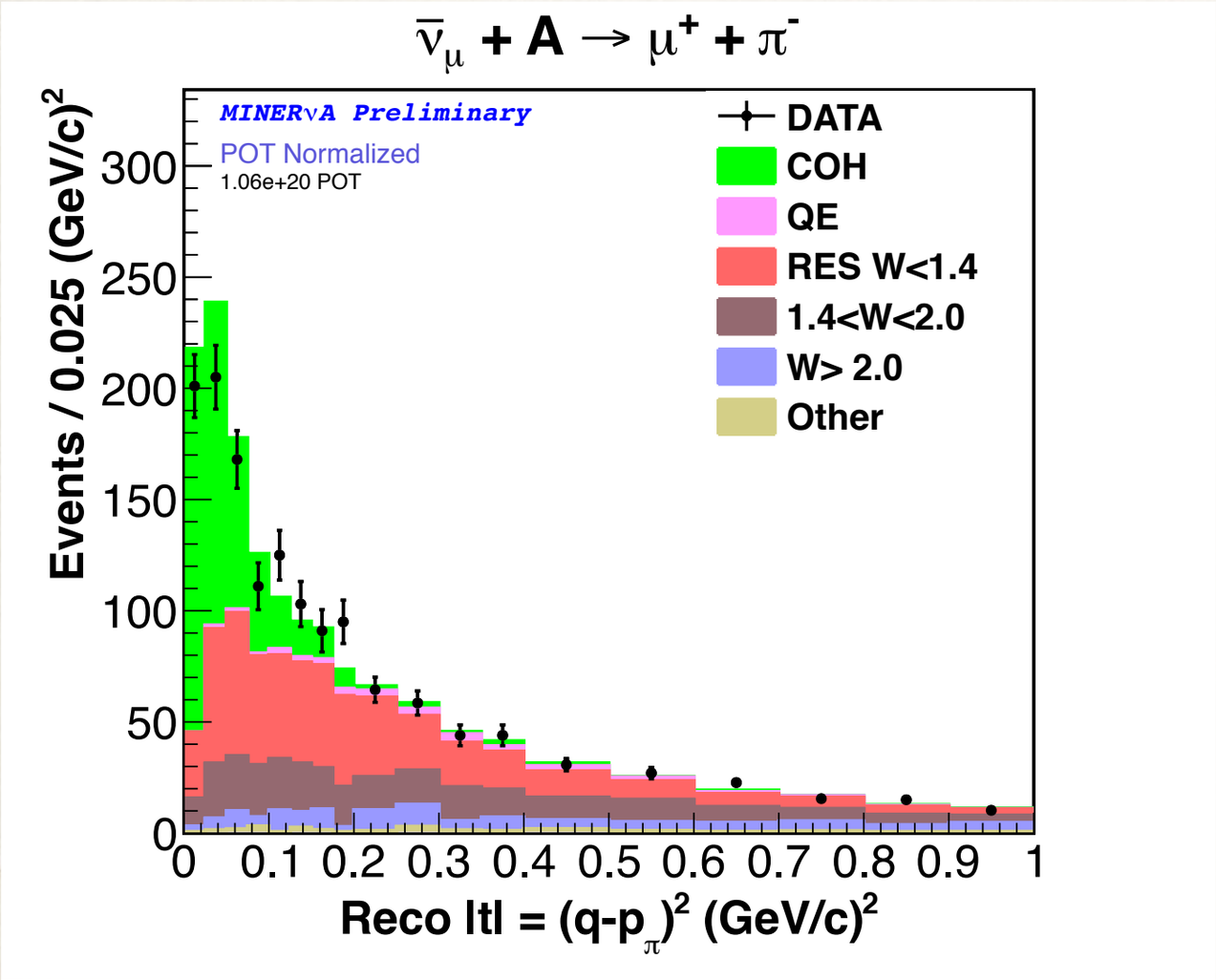


- Clear signal seen by high energy experiments decades ago
- No signal seen in recent high statistics, low energy experiments

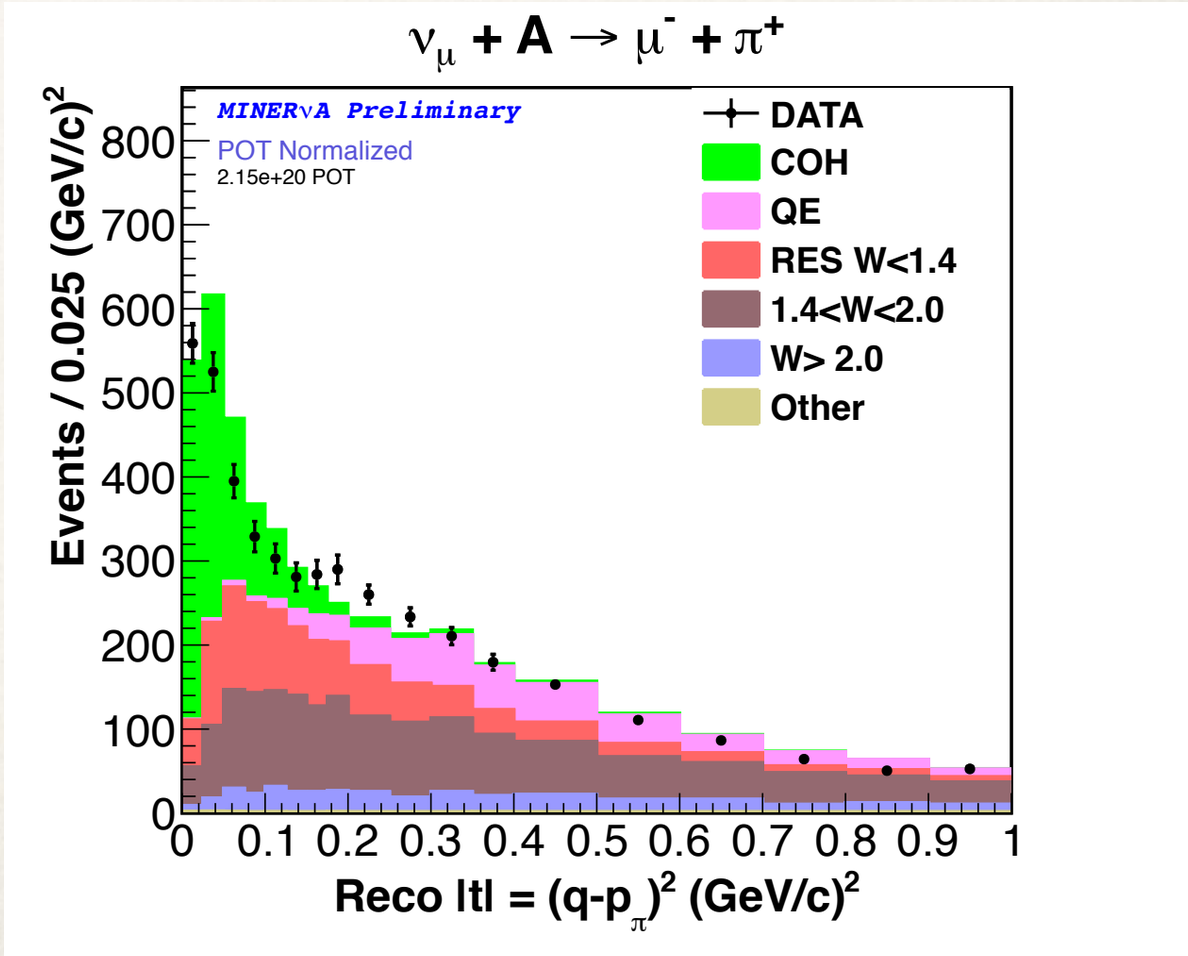




Results: Coherent Pion Production



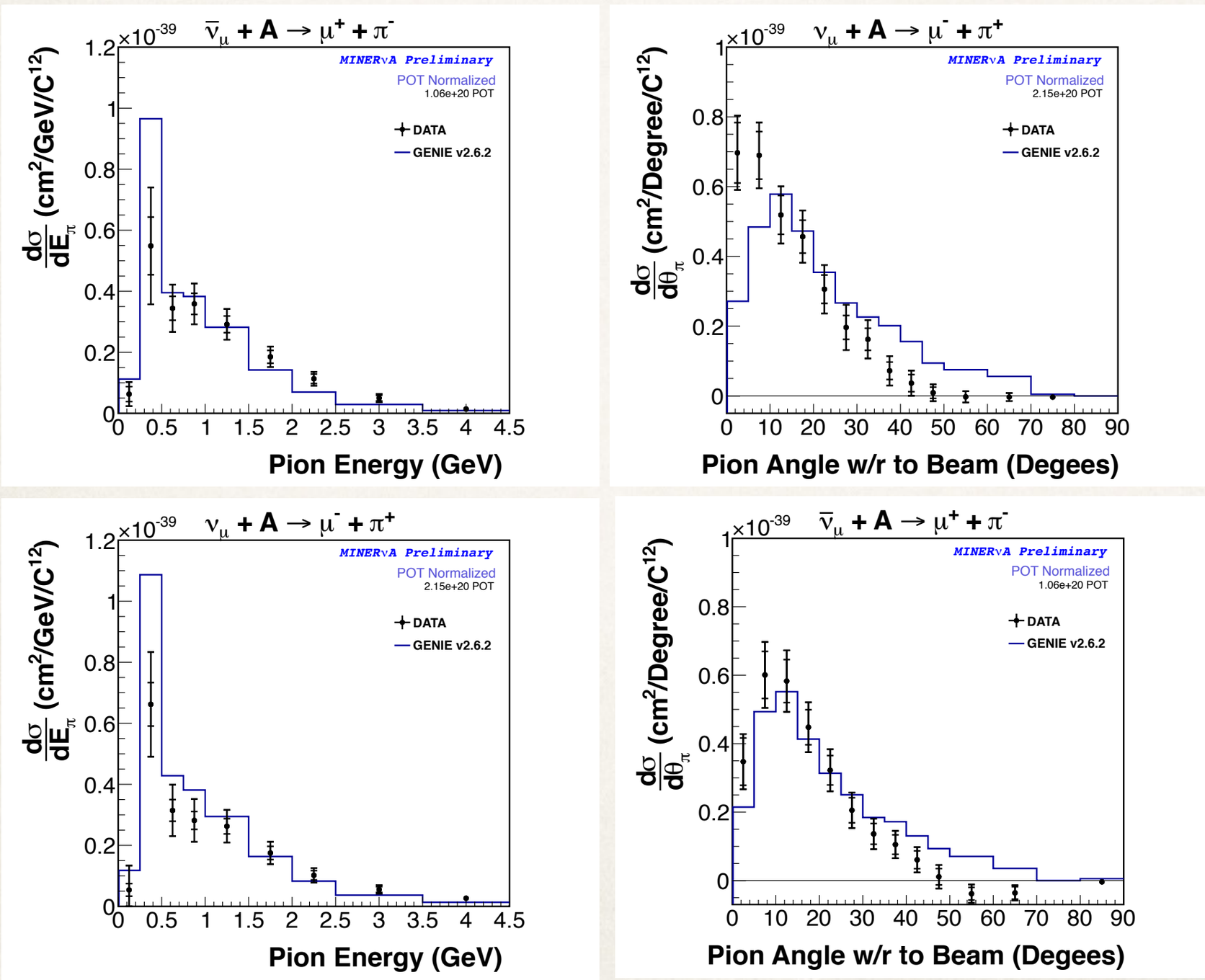
- MINERvA sees clear signal of neutrino and antineutrino coherent pion production



- First measurement to reconstruct |t| (4-momentum transfer to nucleus); minimal model dependence — coherent pion production is predicted to have low |t| across models

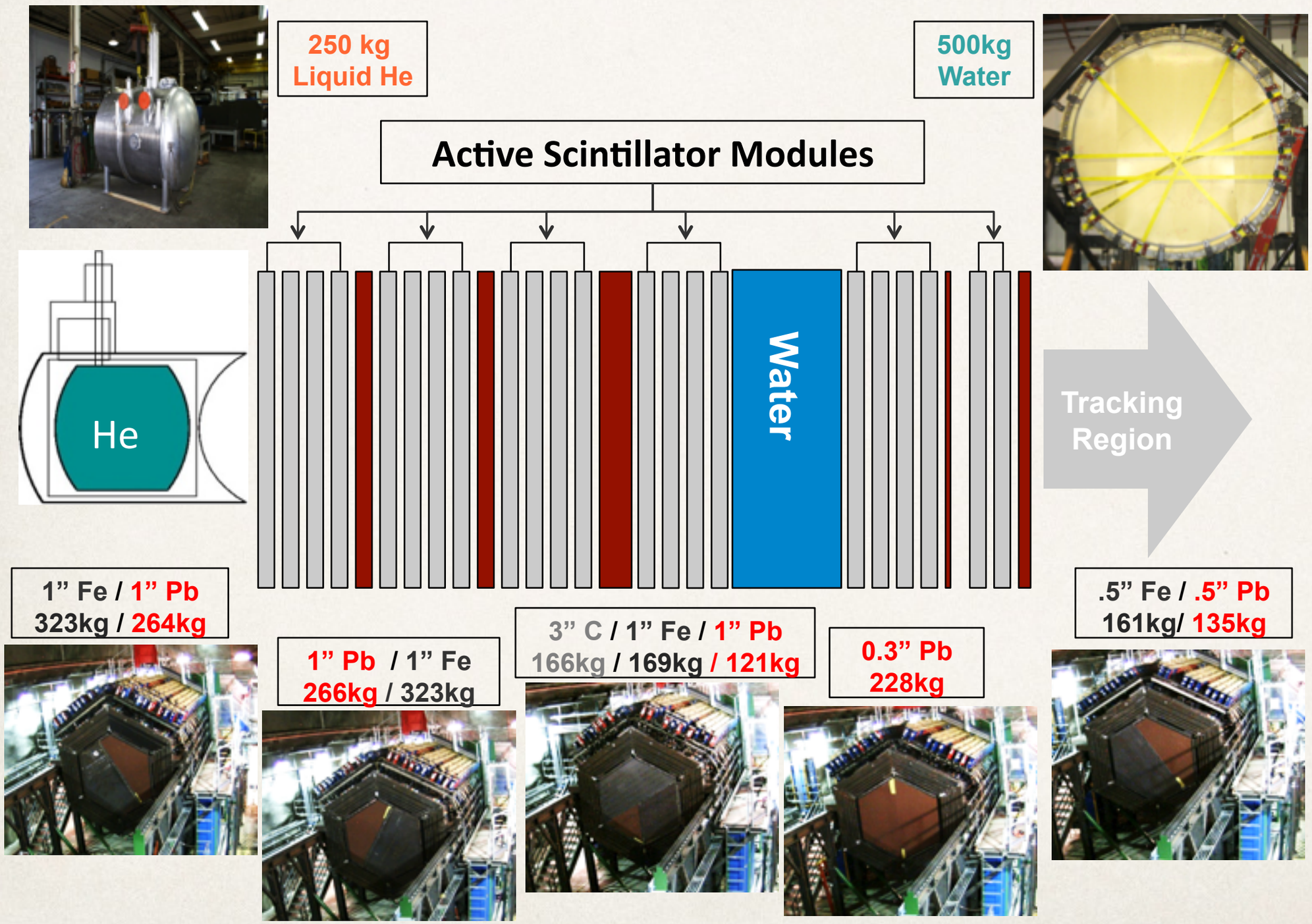
Results: Coherent Pion Production

Cross sections obtained with a cut on |t|:



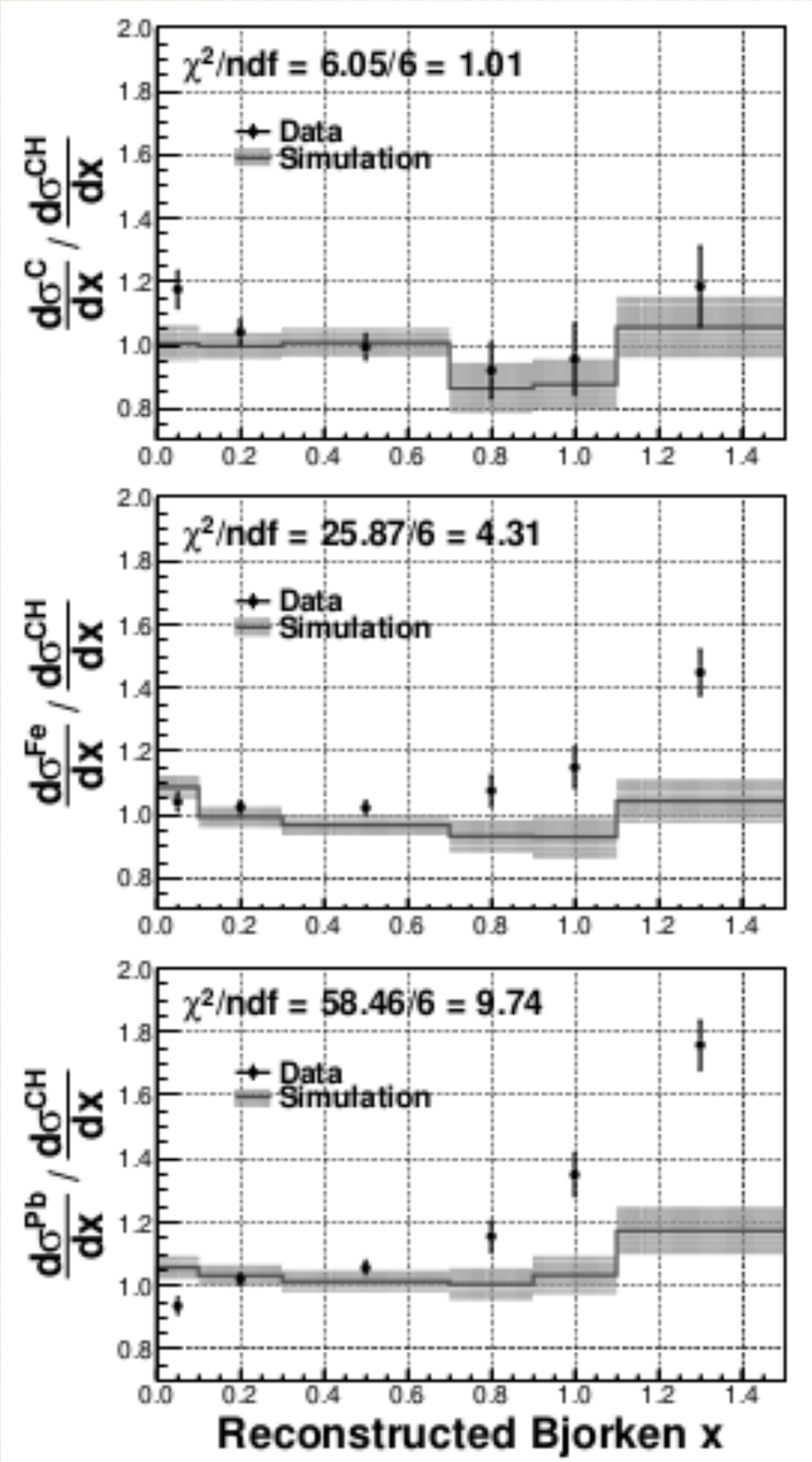
- Can begin to probe kinematic predictions of commonly used model with this signal
- See indications that model does not accurately reflect energy or angle of pion
- Analysis will be ready for publication this year

Results: Inclusive Target Ratios



MINERvA has also begun to study the ratio of neutrino interactions on different nuclei using solid nuclear targets.

Results: Inclusive Target Ratios



Carbon

Iron

Lead

- Inclusive charged current cross section ratios of a dimensionless scaling variable called "x"
- x corresponds to the fraction of the initial nucleon's momentum that is carried by the struck quark
- Large normalization uncertainties cancel in ratios

$$x = \frac{Q^2}{2M\nu}$$

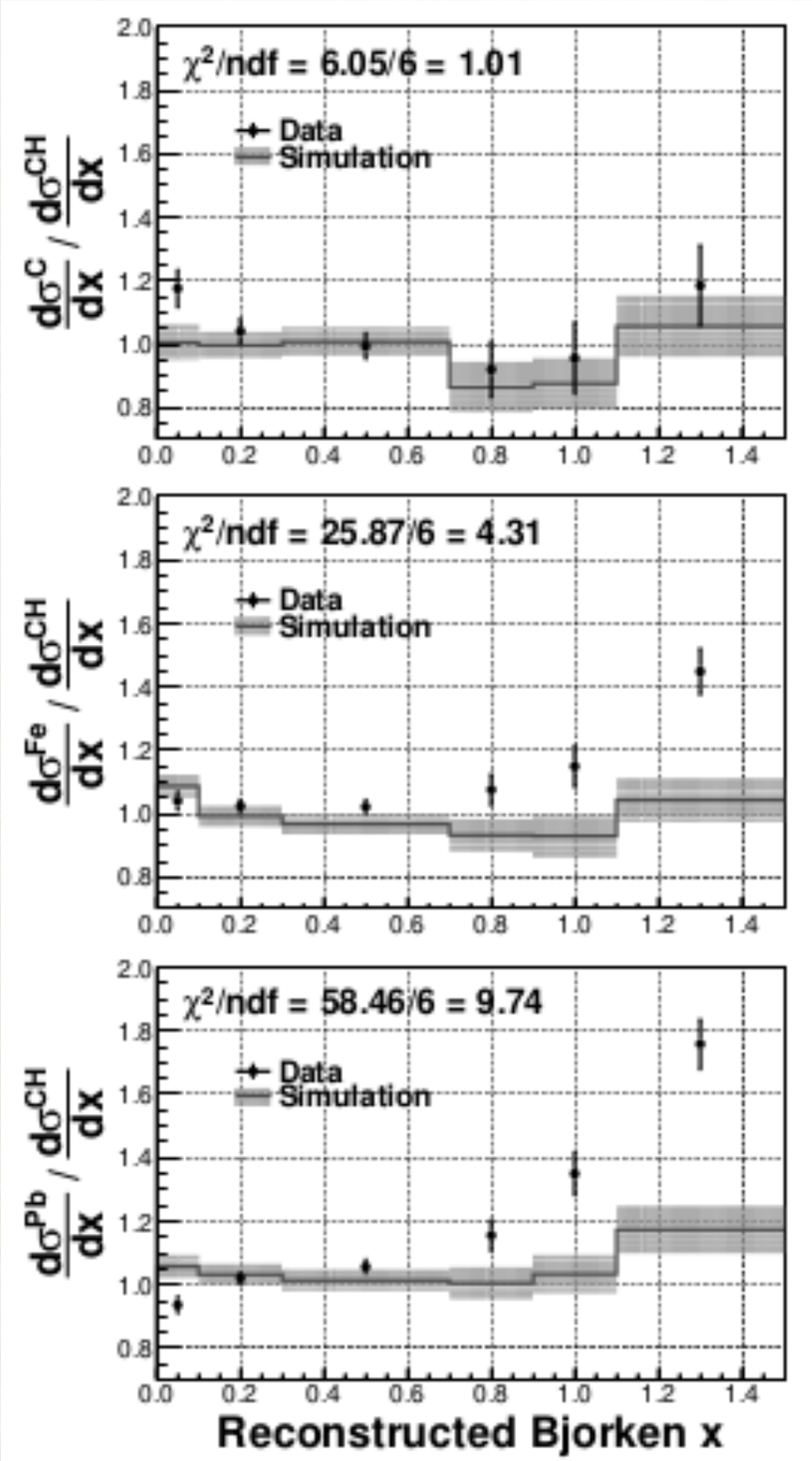
high x = more elastic

$$\nu = E_\nu - E_\mu$$

$$Q^2 = 2E_\nu \left(E_\mu - p_\mu cos\left(\theta_\mu\right)\right)$$

Published last week! Phys. Rev. Lett. 112, 231801

Results: Inclusive Target Ratios



Carbon

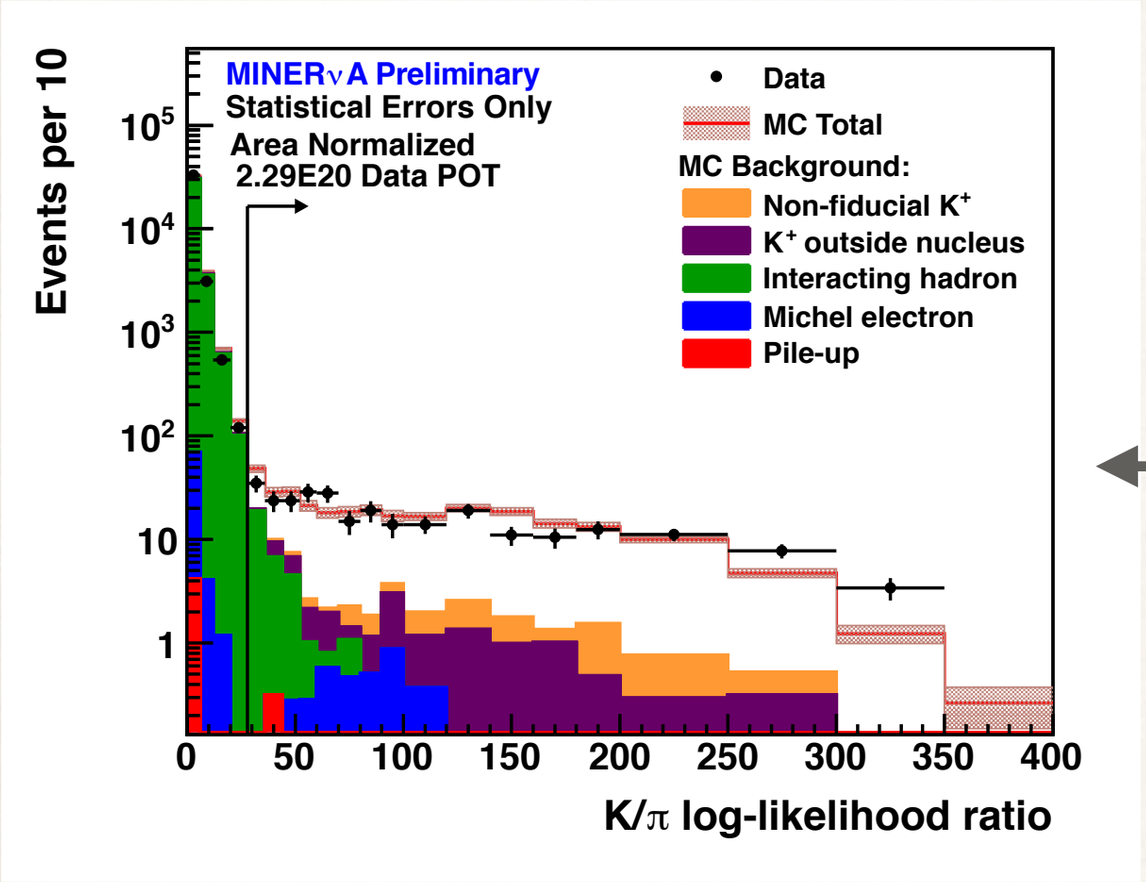
Iron

Lead

- The accepted model of nuclear effects is wrong
- And it is **increasingly wrong in heavier nuclei**
- Important for oscillation experiments: nuclear modifications for heavy elements (e.g. Argon) need work
- And not just important for oscillation experiments
  - This is **physics we don't understand**

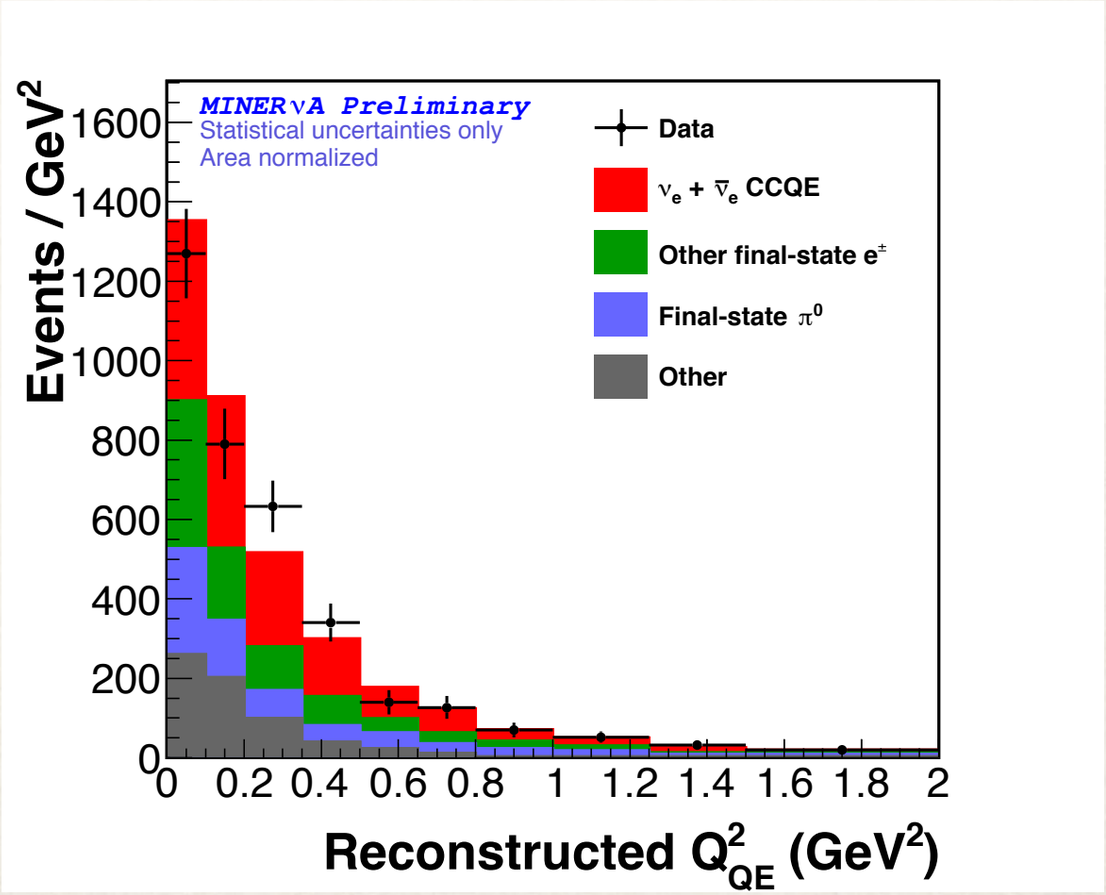
Published last week! Phys. Rev. Lett. 112, 231801

Future Plans

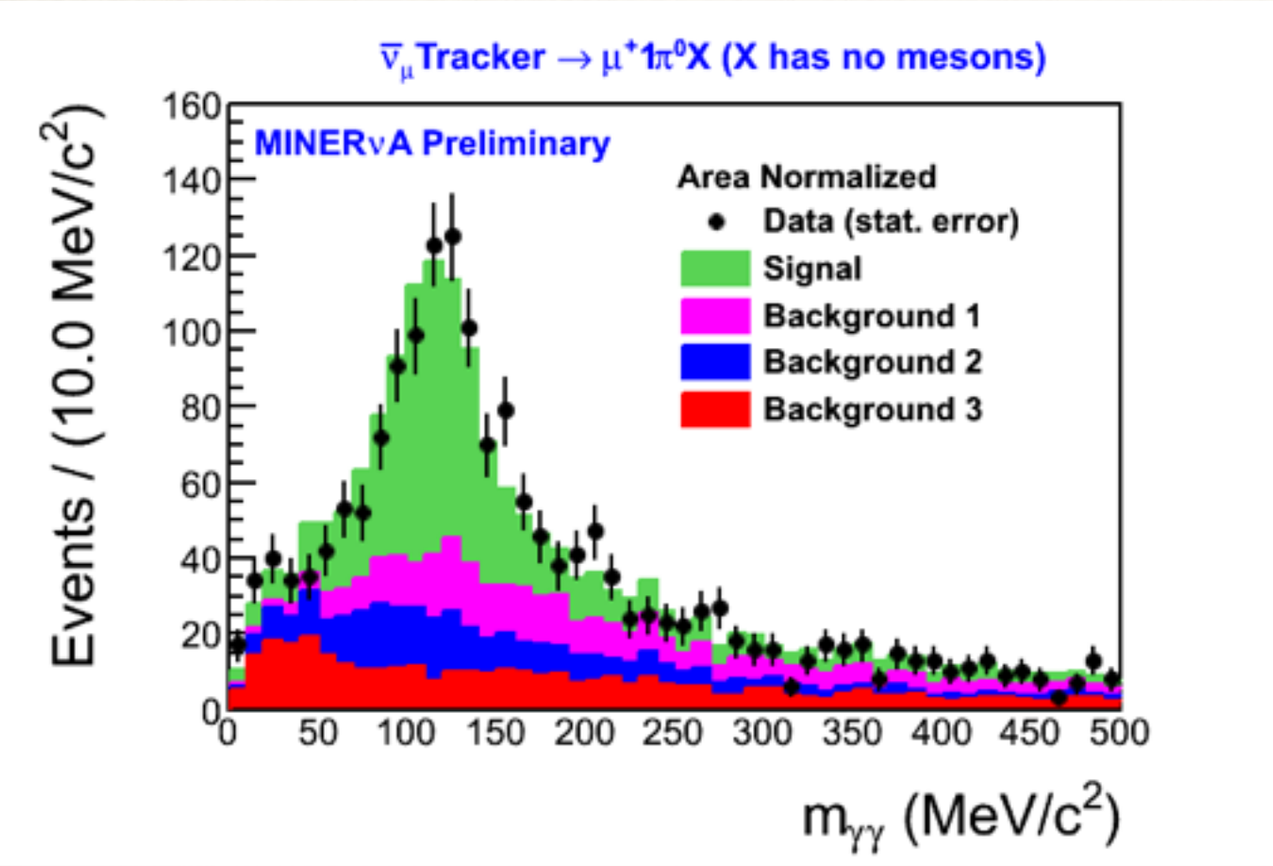


- Kaon production
  - Have already demonstrated good kaon identification via time separation of kaon and decay products

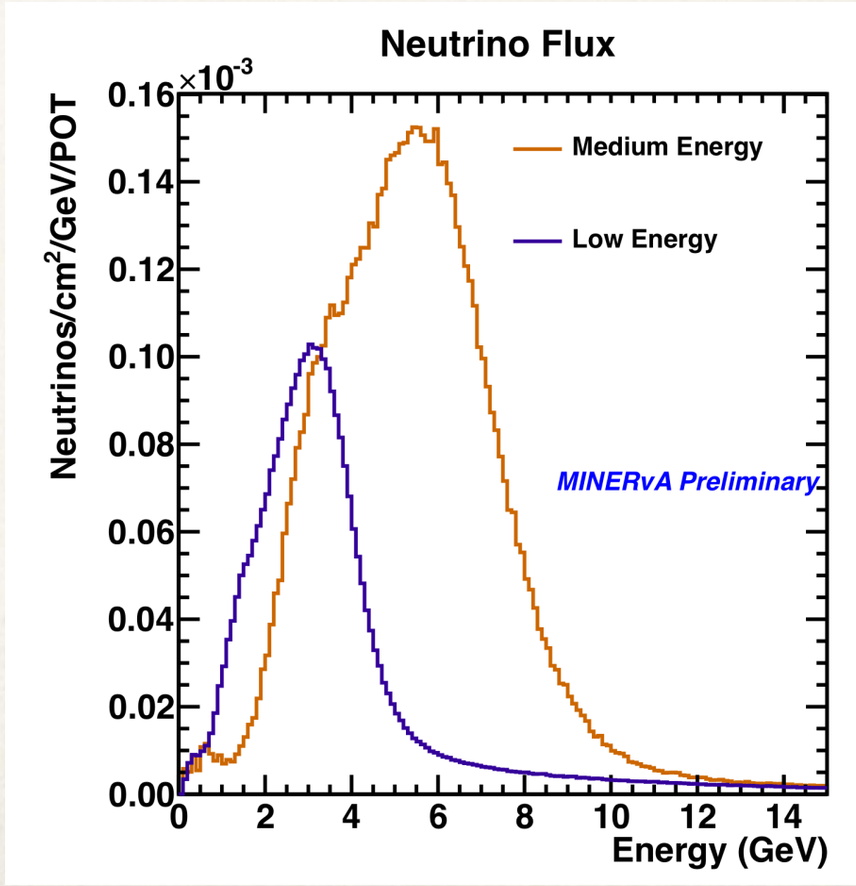
- Electron neutrino quasi-elastic scattering
  - Signal process in ν_e appearance measurements
  - Important test of whether assumptions based on ν_μ scattering hold



Future Plans



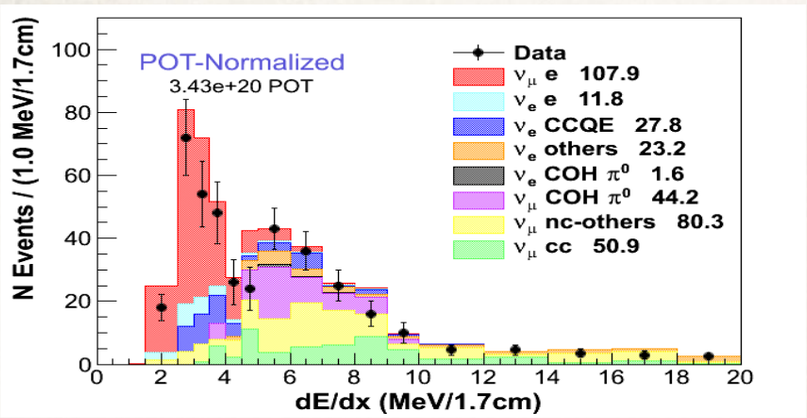
- Neutral pion production
  - Complement to charged pion production studies described earlier
  - Ready for publication this year

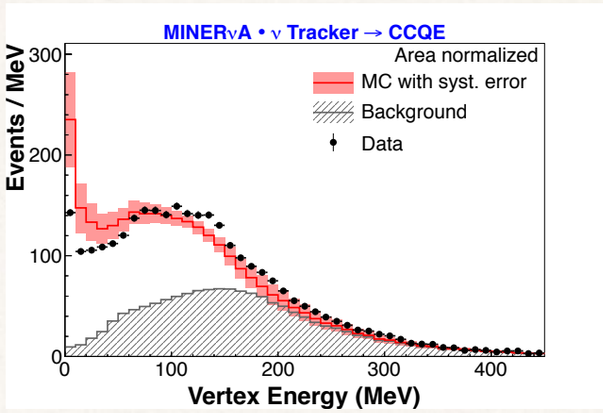


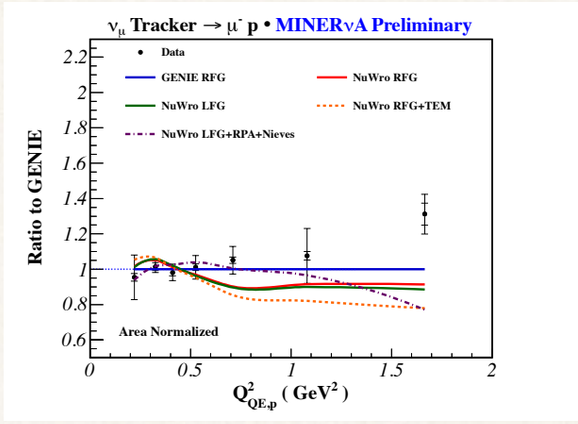
- Many more possibilities with high-statistics medium-energy beam
  - Particularly helpful to statistics limited target ratio analyses

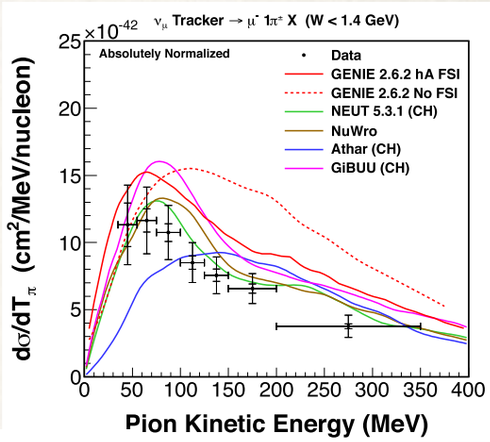
Conclusion

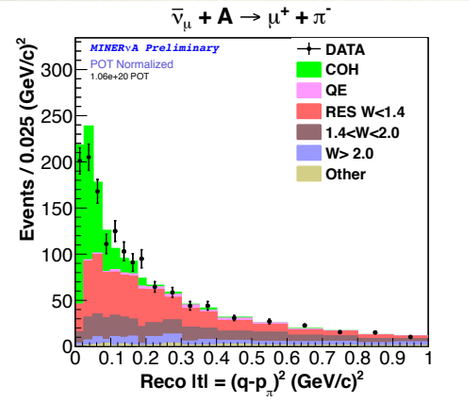
- MINERvA has become a prolific source of neutrino scattering data

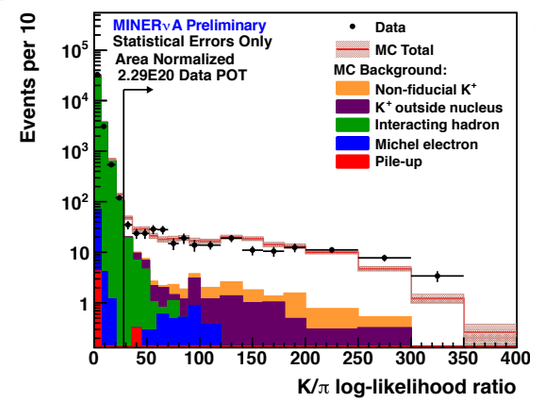


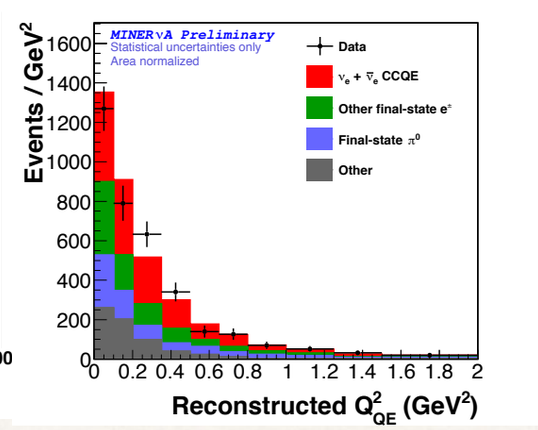


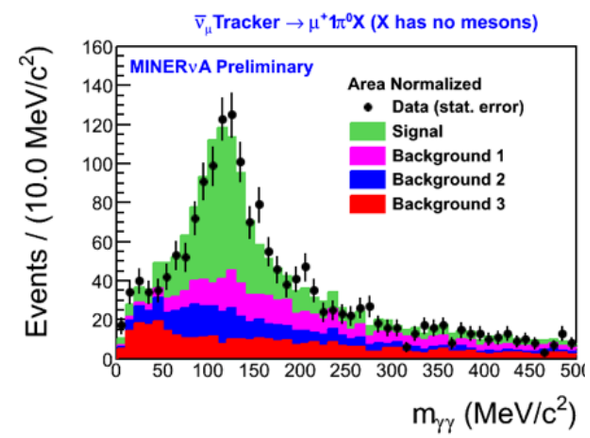


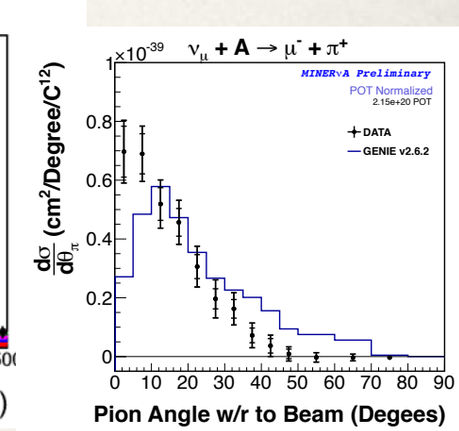












- Our data is illuminating locations where model development is needed

- These precision measurements will provide many of the powerful constraints needed to meet the systematics goals of precision oscillation measurements

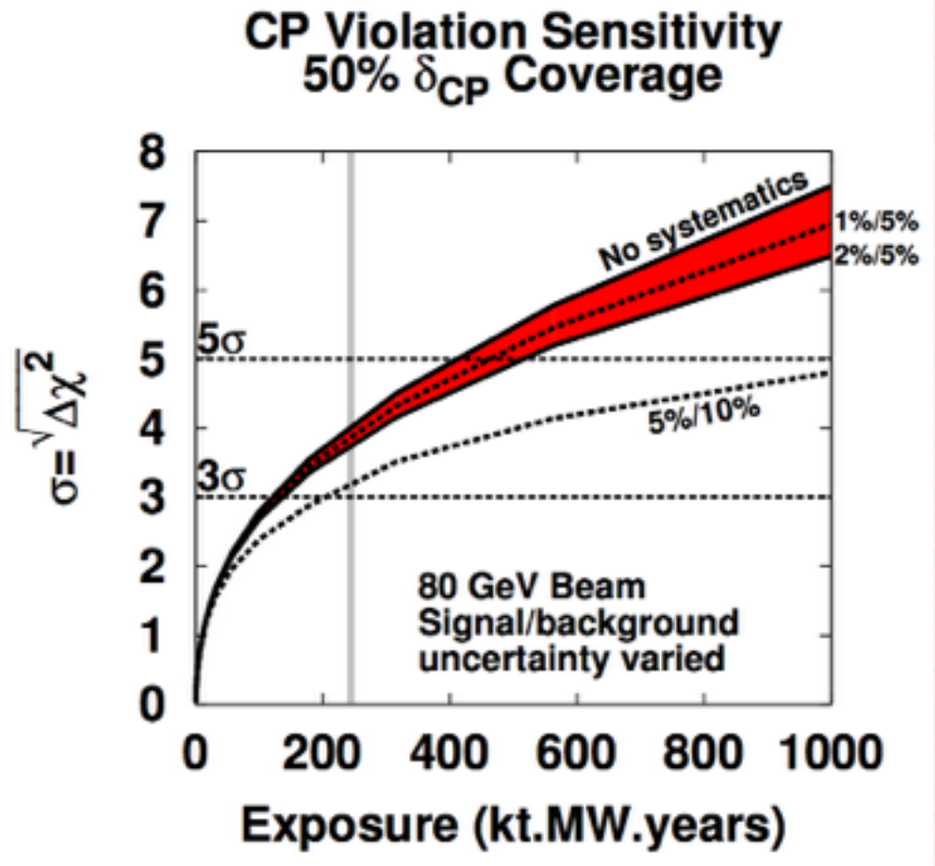
Thank You!

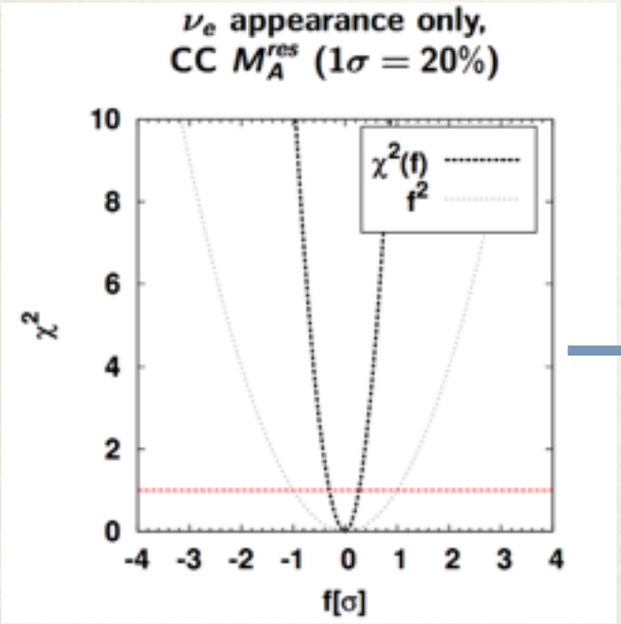
Backup

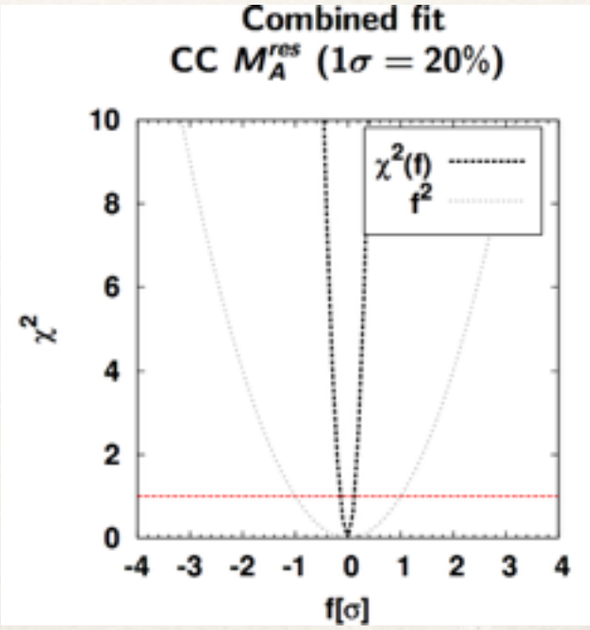
More Details on LBNE Sensitivities

- Uncertainties on rate only; not shape uncertainties considered
- Uncertainties are residual uncorrelated uncertainties on nu_e, nu_e_bar, nu_mu, and nu_mu bar signal and background channels after combined fit to all four channels
- Considering all four channels together significantly reduces systematics

M. Bass NuInt 2014







MIPP/G4NuMI Comparisons